The Hong Kong Polytechnic University

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Optimizing Construction Planning and Scheduling by Virtual Prototyping Enabled Resource Analysis

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis is my own work and that, to the best of my knowledge and belief, it reproduces no material previously published or written, nor material that has been accepted for the award of any other degree or diploma, except where due acknowledgement has been made in the text.

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ABSTRACT

Effective construction planning and scheduling is the first and crucial step towards a successful and efficient construction project. All succeeding tasks, or activities, should follow the planning stage. The planning and scheduling process is arduous, complex and time-consuming. Even experienced construction planners find it impossible to construct a comprehensive and faultless master construction plan, and during construction operations make reviews and updates as necessary. These reviews and updates bring waste and increase the project duration and cost.

A literature review clarifies the definition of construction planning and scheduling and resource planning used in this study is based on current and past approaches related to optimization methods. Conventional computer-assisted technologies such as computer simulation, 4D CAD, Building Information Modelling (BIM), virtual construction, and virtual prototyping (VP) are studied and examined, the aim being to find potential technologies which help to optimize and visualize the construction plans and schedules in order to reduce construction plans, schedules review and update frequency.

The core of the research methodology for this study is action research which helps to develop the framework for integrated planning using VP technology enabled resource analysis. The cyclic process of action research is adopted 1) identification of construction planning and critical issues 2) development of the solution framework 3) implementation and test 4) feedback. Site validation was held during the application of the VP technology. Also, focus group meetings were held at which feedback and comments were collected to enable modifications of the developed VP system to better achieve optimized plans and schedules.

A solution framework was implemented for two case studies representing two different types of project. The first implementation was conducted on a building site to demonstrate the use of a virtual prototyping enabled resource analysis to reallocate space and logistics on an access road and also to arrange tower cranes to achieve a 6-day floor construction cycle. The second implementation applied to a bridge project which demonstrated the use of VP in the design and location of a temporary working platform on a difficult steeply sloping site. The structure for integrated planning was modified to fulfill the needs of the bridge project. In this case study, the temporary platform design and the allocation of plant resources were interdependent.

The results of this research study encourage planners to test the various construction plans using VP system. Better understanding of the construction process and prediction of possible mistakes is enabled. As a result, planners are more able to identify the optimal construction plan.

PUBLICATIONS ARISING FROM THE PHD STUDY

Refereed Journal Papers

1. **Chan, N.**, Li, H., and Skitmore, M. (2012). "The use of Virtual Prototyping to rehearse the sequence of construction work involving mobile cranes." *Construction Innovation: Information*, Process, Management, accepted for publication.

2. Li, H., **Chan, N.**, Huang, T., Skitmore, M., and Yang, J. (2012). "Virtual prototyping for planning bridge construction." *Automation in Construction*, 27, 1-10.

3. Li, H., **Chan, N.**, Huang, T., Guo, H.L., Lu, W., and Skitmore, M. (2009). "Optimizing construction planning schedules by virtual prototyping enabled resource analysis resource analysis." *Automation in Construction*, 18(7), 912-918.

4. Li, H., Guo, H.L., Skitmore, M., Huang, T., **Chan, N.,** and Chan, G. (2011). "Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong." *Construction Management and Economics*, 29(3), 233-245.

5. Li, H., Guo, H.L., Huang, T., **Chan, N.,** and Chan, G. (2010). "An impetus for the construction industry: construction virtual prototyping technology." *Information of China Construction*, (2), 46-51.

6. Li, H., Guo, H.L., Huang, T., **Chan, N.,** and Chan, G. (2010). "Research on the application architecture of BIM in building projects." *Journal of Engineering Management*, (5), 525-529.

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Conference Papers

1. **Chan, N.**, and Li, H. (2009). "Optimizing construction planning and scheduling through combined virtual prototyping technology and building

information models." *Proceedings of the 1st International Conference on Improving Construction and Use through Integrated Design Solutions*, Espoo, Finland.

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LIST OF ABBREVIATIONS

abbreviation

2D	Two-Dimensional
3D	Three-Dimensional
4D	Four-Dimensional (3D plus time)
4DSMM	Four-Dimensional Site Management Model
4D-MCPRU	4D Management for Construction Planning and Resource Utilization
4D-ISPS	4D Integrated Site Planning System
4D Space-Gen	4D WorkPlanner Space Generator
ABC	Activity-Based Construction
ACBM	Activity Cycle-Based Modelling
ACD	Activity Cycle Diagrams
AR	Action Research
AS	Activity Scanning
BIM	Building Information Modelling
CAD	Computer Aided Design
CHASTE	Construction Hazard Assessment with Spatial and Temporal Exposure
CIFE	Centre for Integrated Facilities Engineering
CPM	Critical Path Method
CVP	Construction Virtual Prototyping
CVPL	Construction Virtual Prototyping Lab
DES	Discrete Event Simulation

DIVERCITY	Distributed Virtual Workspace for Enhancing Communication within the Construction Industry
GUI	Graphical User Interface
FGM	Focus Group Meeting
FGM-A	Focus Group Meeting (Team A)
FGM-B	Focus Group Meeting (Team B)
GA	Genetic Algorithm
GA-RACPM	Genetic Algorithm enhanced Resource Activity Critical Path Method
GIS	Geographical Information Systems
HA	Heuristic Algorithm
IFC	Industry Foundation Class
IVE	Immersive Virtual Environment
KM	Knowledge Management
LSM	Linear Scheduling Model
LOB	Line-of-balance
NBIMS	National Building Information Modelling Standard
PE	Project Engineer
PERT	Program Evaluation and Review Technique
PM	Project Manager
RACPM	Resource-Activity Critical-Path Method
RISim	Resource-Interacted Simulation
RM	Resource Management
S3	Simulation-based Scheduling System
SQL	Standard Query Language

VBA	Visual Basic for Application
VCE	Virtual Construction Environment
VDC	Virtual Design and Construction
VFP	Virtual Facility Prototyping
VR	Virtual Reality
VP	Virtual Prototyping

CHAPTER 1 INTRODUCTION

1.1 Introduction

Construction planning and scheduling is fundamental to the process of construction management to determine satisfactory use of the time available, cost, quality and protection of the environment. This PhD study aims to find a way to optimize the planning process. This chapter provides an overview of the thesis and hence includes the background of the research, the research problem, the research objectives, the research methodology and the research significance .The structure of the thesis, which comprises eight chapters, is outlined.

1.2 Background to the Research

Careful planning, proper execution of the work on site and the use of established techniques are three critical factors that enable construction projects to be successfully completed. The planning and design of construction plans in relation to such as arrangement of resource and space is the first and crucial step from which all other tasks, or activities, follow and which therefore lead to successful project completion. Project planning and design, in the current form, is an arduous, complex and time-consuming task. Improvement in this regard would contribute to develop the solution framework enabling optimized construction planning and scheduling for buildings and bridge projects. And would therefore be welcomed.

Forming a construction plan is a challenging task. As Sherlock Holmes noted:

"Most people, if you describe a train of events to them, will tell you what the result would be. They can put those events together in their minds, and argue from them that something will come to pass. There are few people, however, who, if you told them a result, would be able to evolve from their own inner consciousness what the steps were which led up to that result. This power is what I mean when I talk of reasoning backward." (Doyle 1930)

Construction planners and detectives are similar in the ways in which they establish how their work should be carried out. Both professions start with an appraisal of the final product or situation. They then investigate the steps that could be taken to reach it. Fundamental to construction planning is the choice of a feasible construction methodology and activities sequence, Construction planners need to weigh the pros and cons of various factors such as time, cost and quality to choose the most suitable plan. They have to create images of the finished product by utilizing descriptions in the construction plans and specifications.

In developing a construction plan, the critical path method (CPM) and bar charts, are commonly used to enable construction projects to be conducted in a systematic way. This method involves the project team allocating the required resources associated with the major selected method and deciding on the appropriate task assembly sequence. However, contractors' project planners face many uncertain and complex tasks during the construction period due to such as, design errors and mismatch of that which has been planned and that which is needed in practice (Li et al. 2008a). In addition, errors and mistakes in construction planning and scheduling occur frequently as their compilation depends, to a large extent, on the particular limits of the project team's knowledge and experience (Waly and Thaet 2002). Even experienced construction planners find it impossible to build/design a comprehensive and faultless master construction plan at the first attempt, consequently reviews and updates are always necessary. These reviews and updates, obviously, are wasteful and costly, as regards the amount of time spent. Therefore, for the main contractor, a successfully tendered building project can be very much a gamble due to the main contractor’s inability to predict whether the project will result in a profit or a loss in advance of construction.

For many projects, a major limitation affecting the planning process is the lack of effective computer-assisted technology to help with the resource allocation. Due to the complexity and the large number of factors involved in the above, computers can be an efficient tool to help project planners. Such basic computer aids as bar charts and the critical path method are quite limited as they are unable to provide spatial images of construction features or resources and working space requirements (Koo and Fischer 2000; Chau et al. 2003). More sophisticated methods combine the three traditional techniques of resource allocation, resource levelling and time-cost trade-off analysis. For example, Chan et al. (1996), Hegazy (1999), Leu and Yang (1999a) combine resource allocation and levelling using genetic algorithms (GAs); Li and Love (1997) propose GAs for time-cost optimization problems; Hegazy and Kassab (2003) combine a flowchart based simulation tool with the GA technique. Wang et al. (2004) developed a 4D Management for Construction Planning and Resource Utilization (4D-MCPRU) system which links a 3D geometrical model with resources, such as material, equipment, labour to obtain the necessary resource requirements. One of the shortcomings of the above effective computer-assisted technology project planning and resource allocation methods is that they did not take the real productivity rate of different plant items and manpower into account.

The inherent uncertainty and complexity of construction work make construction planning a particularly difficult task for project managers due to the necessity to anticipate and visualize likely future events. Rehearsing practical operations is without doubt one of the most effective methods for minimizing planning mistakes because of the resulting opportunity to learn from what takes place during such rehearsal activities. However, real rehearsal is not a practical solution for on-site construction activities as it involves high financial cost as well as not being environmentally friendly.

Mission rehearsal ideas, such as Virtual Prototyping (VP) exist in many areas of human endeavour, including education (e.g. Hill et al. 2003), medicine (e.g. Cates et al. 2007), fire fighting (e.g. Tate et al. 1997), underwater exploration (e.g. Davis and Brutzman 2005), military (e.g. Rickel et al. 2002), psychology (e.g. Marsella and Gratch 2001), and have been a common concept in the manufacturing industry for a long time (Aust and Dunlap 2002). Mission rehearsal ideas have, however, has received little attention to date in the construction industry. The main reasons for this appear to be that 1) the budget for the prototype of a building involves a substantial amount of monetary and human resources, 2) each construction project is unique in terms of location, constraints and requirements, 3) the limited amount of construction time available and 4) the lack of an effective computer-assisted technology for construction planning and scheduling.

VP technology presents great potential in the construction industry. Currently, VP technology assists project planners to identify construction methods and prepare construction schedules (Li et al. 2008b). VP offers an improved way of planning through the visualization of construction activities by computer simulation, enabling a range of 'what-if' questions to be asked, with implications on the total project investigated.

1.3 Research Aim and Objective

The aim of this research project is to develop an integrated planning approach for optimizing construction planning and scheduling using VP technology. The specific research objectives of the study to achive this aim, are as follows:

1) To investigate the existing methods used in the research domain and industry for improving the planning process i.e. of optimizing construction plans and schedules;
2) To identify the resource analysis necessary to conduct construction planning and scheduling;
3) To design a follow-through research methodology (i.e. the combination of research methods e.g. focus group meeting, case study and site validation) for this research applicable to real case projects;

4) To develop a framework for the integrated planning using VP technology;
5) To assist construction planners to plan and improve the accuracy of the planning by rehearsing the plan and analyzing it.

1.4 Research Design and Methodology

In order to achieve the research goals, action research is utilized into the whole structure of the research throughout the course of this study. The structure of action research design is achieved through a cyclic process with five distinct steps including diagnosis, action planning, action itself, evaluation, and specific learning (Susman and Evered 1978). A combination of research methods including literature reviews, focus group meetings, case studies and site validation (which is a novel approach research method. The details of the approach are described in Section 3.6) would be used in the action research.

The research design is described below: (the flowchart of the research is shown in Fig 1.1.)

Diagnosis: A literature review and a focus group meeting are involved in this area. The research gap is made clear through the results of an analysis of the research in the area of current construction planning and the practice of it. Manufacturing methods (i.e. virtual prototyping) are studied to ascertain their relevance and value to construction planning. Holding focus group meetings is a way of efficiently collecting comments from experienced construction staff to assist in the development of frameworks for integrated planning.

Action Planning: The action research involved is based on the data collected during the diagnostic stage, a solution framework is developed based on that data. The framework enables resource analysis such as the positioning of space, forms and amount of equipment and crew numbers. The existing application (i.e. virtual prototyping) is selected to support the solution framework.

Action Taking: Case studies are an important and effective method to demonstrate the effects and implications of relevant research study. In the present research study, two different types of construction project case studies were used to test the feasibility and validity of the solution framework for optimizing construction plan. For each case study, the researcher worked with planners or engineers in the construction site office during the whole development of VP system (2 to 4 months). The steps considered are as follows: 1) collaborate with project staff and obtain feedback regarding the feasibility of VP system and problems met, 2) adjust the framework to achieve the critical issues found, 3) implement and test the framework and 4) provide a platform to test various construction plans. Data were collected from the focus group meetings to verify and test the VP system.

Evaluation and Learning: The focus group members evaluate the effectiveness of the system. Their feedback is collected for further improvement of the whole research and also used as a starting point for further research.

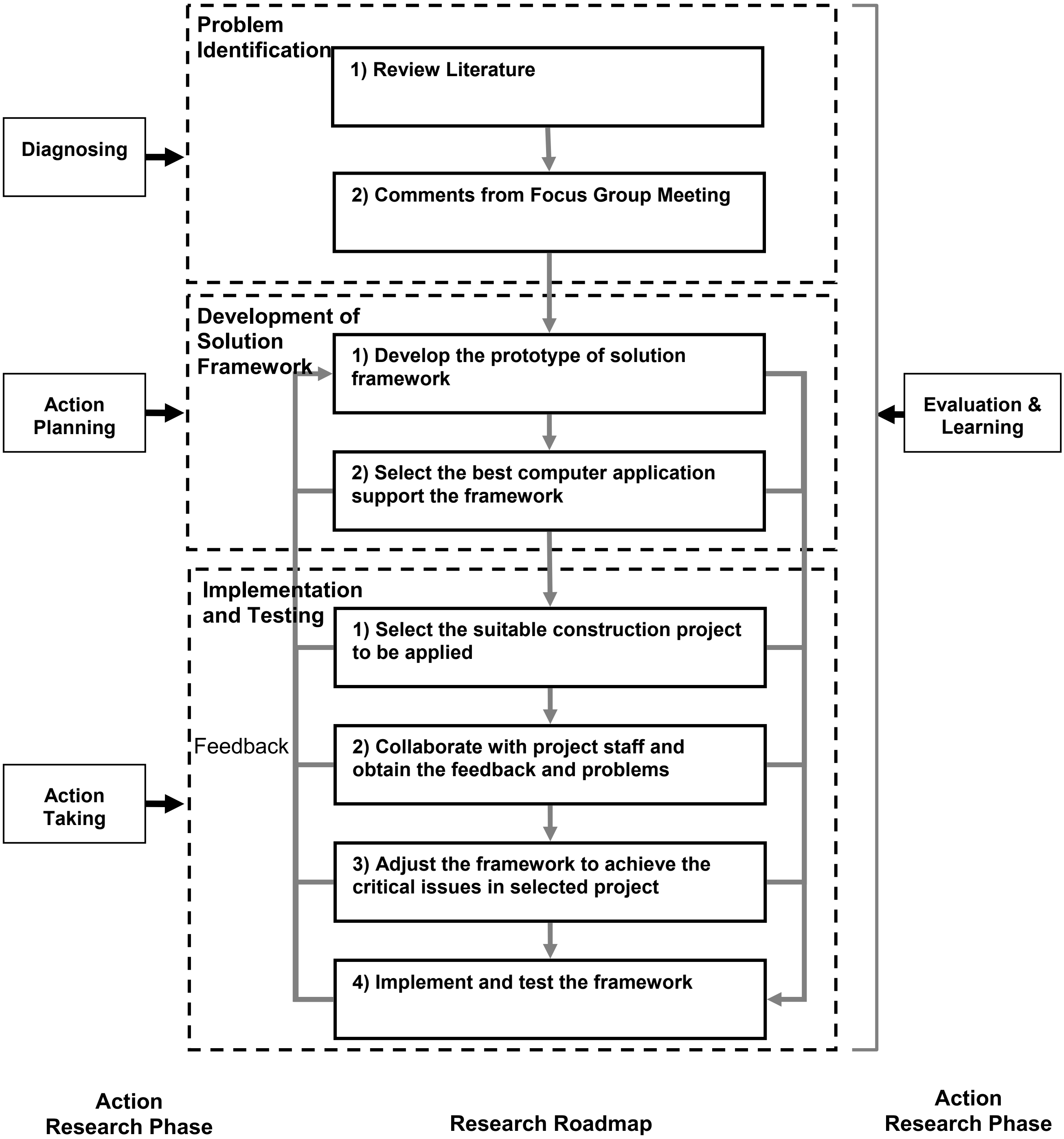


Fig 1.1 Research methodology framework

1.5 Significance of the Research

This research study has made a contribution towards enabling construction planners to better optimize construction planning and scheduling. Through the results from a comprehensive examination of the relevant literature and focus group meetings the key factors of construction planning and scheduling have been better understood and a solution framework developed. By using the approach described above, a project can be rehearsed before construction based on matters learned by the repetition or rehearsal of schedules. Project planners hence are assisted to better understand the construction processes and predict any potential problems caused by mistakes discovered in the planning.

To achieve the research aim and objective, several contributions to project planning are made through the processes listed below:

1) Utilization of the characteristics of Building Information Modelling (BIM) to embed specification and productivity data in plant models
2) Decomposition of BIM models for scheduling and a detailed simulation to make the 3D model and schedule match in pairs
3) Construction plant and equipment database to reuse the construction plant and equipment on other construction projects
4) Development of a model of the relationships between the proposed-built model, site layout planning (i.e temporary work design) and plant and equipment-resource allocation in construction planning
5) Combination of the project level and operational level as two distinct levels of detail of the visualization and models of construction processes (Kamat and Martinez, 2003) in construction planning and scheduling

6) Enablement of resource analysis in construction planning and scheduling to make the planning a more comprehensive
7) The adoption of site validation in the research method to improve the development efficiency of the research
8) The provision of a VP system platform for the planners to test various construction plans (optimization process)

1.6 Structure of the Thesis

Chapter 1 introduces the background of the research, research problems, research objectives, research methodology, significance and the structure of the thesis.

Chapter 2 presents a literature review on the construction planning and scheduling, resource planning, 4D CAD, Building Information Modelling and VP technology. It covers various planning techniques and isolated research gaps during the review.

Chapter 3 introduces the research methodology used in this study. The research methods include a literature review, focus group meetings, case studies, site validation and action research. The action research acts provides a map for the research procedure. The literature review, focus group meetings, case studies and site validation form different parts of the action and make the research methodology more comprehensive.

Chapter 4 describes the framework for VP technology integrated planning. Through evaluation of the previous research and resource analysis comments such as on productivity rate required regarding construction planning and scheduling, the solution framework is developed to suit the needs of building projects.

Chapter 5 demonstrates the feasibility and validity of the application of the VP approach to construction planning and scheduling by using a real-life building project. Feedback from the focus group meeting is also collected.

Chapter 6 concerns the development of the proposed framework to suit the needs of a bridge project. The development and validation process of the system and feedback from the focus group meetings are presented in the chapter.

Chapter 7 demonstrates the feasibility and validity of the modified application of the VP approach to construction planning and scheduling. A bridge project is used as a real-life case study project.

Chapter 8 summarizes this PhD thesis with knowledge contributions highlighted. Recommendations for further research are also addressed.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The definition of construction planning and scheduling and the factors which lead to success in these activities are reviewed in this chapter. Deficiencies in ways in which construction planning and scheduling and resource management have been determined based on a review of both the current and past literature related to computer simulation, 4D CAD, Building Information Modelling (BIM). Virtual construction and Virtual Prototyping (VP) technology have been studied and investigated to find techniques with the potential to support the approach proposed in this study, for optimizing construction planning and scheduling.

2.2 Construction Planning and Scheduling

Construction planning can follow two directions almost simultaneously (Hendrickson, 1998): one is cost-oriented which leads to direct and indirect cost control; another is schedule-oriented which controls time and resource consumption (Figure 2.1). Construction scheduling is incorporated in construction planning and deals with more specific factors such as maintenance of task precedence (resulting in *critical path scheduling* procedures), or efficient use of resources over time (resulting in *job shop scheduling* procedures). In most complex projects, both cost-oriented and schedule-oriented planning are considered.

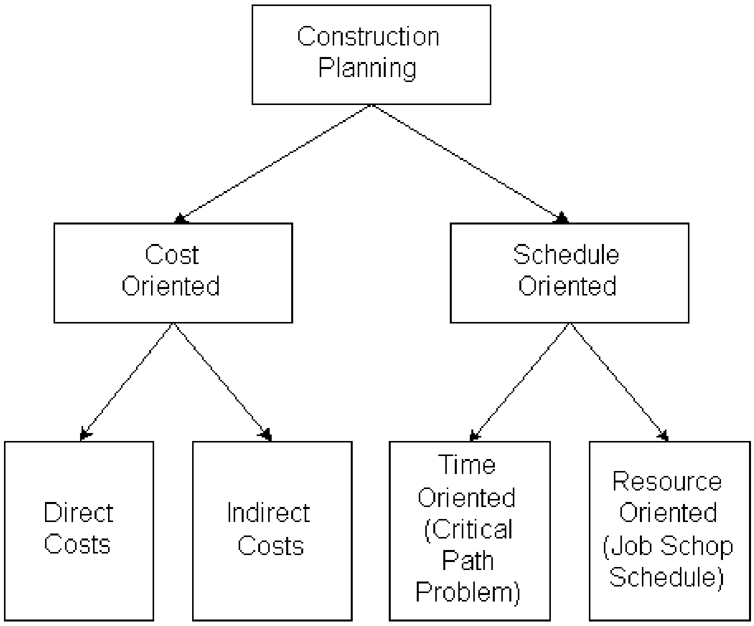


Figure 2.1 Alternative emphasis in construction planning (Hendrickson 1998)

2.2.1 Definitions of Construction Planning and Scheduling

The Collins English dictionary (McLeod 1986) defines planning as: "a detailed scheme, method, etc for obtaining an objective". Mawdesley et al. (1997) extend this definition to define planning as "a general term which is used to encompass the ideas which are commonly referred to as programming, scheduling and organizing. These definitions when applied to the building industry can combine to present an aim that may be defined as: "to make sure that all work required to complete the project is achieved in the right order, in the right place, at the right time, by the right people, with the right equipment, to the right quality, and in the most economical environmentally acceptable manner." Planning should not be confused with scheduling; that is the understanding and production of a set of sequenced construction activities.

Patrick (2004) regarding "*Construction Project Management*" states that

"*The planning, scheduling, evaluation, and controlling of construction tasks or activities to accomplish specific objectives by effectively allocating and utilizing appropriate labor, material, and time resources in a manner that minimizes costs and maximizes customer/owner satisfaction.*

Planning a construction project is an essential activity in which techniques are selected, project tasks are defined, and resource requirements and constraints are identified. Construction planning prepares for the efficient application of project resources.

Scheduling involves arranging project tasks and resources in a sequence to minimize the use of resources, specifically time and money, and maximize quality and customer/owner satisfaction."

Hancher (2003) in The Civil Engineering Handbook writes that

"One of the most important responsibilities of construction project management is the planning and scheduling of the construction project. Planning for construction projects involves the logical analysis of a project, its requirements, and the plan (or plans) for its execution. This will also include consideration of the existing constraints and available resources that will affect the execution of the project. Considerable planning is required for the support functions for a project, material storage, worker facilities, office space, temporary utilities, and so on. Scheduling of construction projects involves the determination of the

timing of each work item, or activity, in a project within the overall time span of the project."

As indicated above, construction project planning and scheduling are key elements of successful construction project management. Planning and scheduling are closely related to achieve good construction project management.

2.2.2 Traditional Construction Planning and Scheduling Methods

2.2.2.1 Gantt Chart

All projects require both planning and scheduling if their design and production are to be successfully monitored and controlled. Prior to Henry L. Gantt, planning and scheduling were undertaken without formal processes or methods. Gantt introduced the "Gantt Chart" now commonly referred to as the bar chart, as a basis for scheduling production activities and this form of communicating the schedule of construction continues to be used for most if not all construction projects. Even the advanced planning and modelling techniques that are incorporated within today's Project Management Systems adopt the bar chart as a means for presenting their results.

2.2.2.2 Critical Path Method (CPM)

The critical path method (CPM) is commonly used to better enable the construction planning and scheduling of construction projects to be systematic (Koo and Fischer 2000). This involves the project team deciding the appropriate sequence of assemblies when allocating the different resources needed for the major method selected. Many construction planning and scheduling software packages exist in the market such as Primavera, Open Plan, Harvard Project Manager and Microsoft Project. CPM schedules are typically used to provide an overall view of the project, activity duration, sequences, milestones and criticality of activities.

CPM focuses on precedence relationships among activities and computes project duration in deterministic terms by analyzing which sequence of activities has the least float capacity. Early start and finish times of an activity are computed, using a forward-pass-algorithm, and late start and finish times of an activity using a backward-pass-algorithm (Moder et al. 1983; Barrie and Paulson 1992; O'Brien 1993; Patrick 2004). The CPM algorithm defines the path (sequence of activities) that provides the shortest project duration, among all possible paths. The main outputs are the range of possible activity times, critical activities and floats, and cost and resource information related to activities.

The CPM technique, although a powerful planning and scheduling tool, has limitations. They are as follows.

1) A greater number of activities and relationships are involved in CPM schedules for operations planning, hence it is harder to manage, maintain and track the progress of construction program. Though with the use of Program Evaluation and Review Technique (PERT) networks in operations, the greater the number of sequencing relationships, the higher the chances of schedule inconsistencies (Waly and Thabet 2002).

2) CPM does not consider the resource utilization by assuming resource quantity (Peer 1974; Laufer and Tucker 1987; Leu and Yang 1999b; Lu and Li 2003; Zhang et al. 2006b). It is not possible to plan and optimize resource allocation by adopting only the CPM method. Seamless synchronized activity planning and resource planning, the two integral functions in project planning are not possible.

3) CPM activities are not representations of construction production characteristics. Although the CPM activities are the fundamental units used for schedule analysis and with the aggregations of the units, a set of construction processes can be formed, the details of how these processes are performed, are missing.

4) CPM does not contain dynamic and stochastic characteristics of construction projects due to its deterministic and static representation nature (Halpin and Riggs 1992; Sawhney and Abourizk 1995).

5) The critical path method is unable to provide spatial construction features or resources and working space requirements (Koo and Fischer 2000; Chau et al. 2003).

6) The CPM networks fail to show the work activity progression of parts of the wider workflow. The way for the CPM networks to demonstrate the often repetitive operations of activities in most construction projects is difficult to handle, in terms of scheduling, as it often contains several exact or similar work units. This feature presents a problem as CPM has a need to show all activity

units and all linking arrows, leading to a very large and complicated network (Senior 1995; Harris 1998; Senior and Halpin 1998). For repetitive network projects such as skyscrapers and highways, which possess a geometrical linear nature, Line-of-balance (LOB) techniques and linear scheduling method have been developed to resolve their respective work activity progression of parts of the wider workflow (Vorster and Bafna 1992; Harris 1996).

2.2.2.3 Look-ahead schedules

In order to overcome the limitations of CPM schedules for operations planning, a usual practice in the construction industry is to utilize *look-ahead* or *short-interval* schedules to show near-term activities (commonly a two or three week range) which possess more details than the master schedule. In the past, a number of research studies have pointed out the value and the need for look-ahead schedules (Ballard 1997; Hinze 1998). However, problems are found with the look-ahead schedules as they are prepared by hand or used as a set of heuristics from the master schedule and resource input, resulting in inconsistency between the master schedule and the look-ahead schedule.

Look-ahead schedules are akin to the CPM networks which do not relate explicitly to spatial aspects of a project. If spatial interactions are crucial aspects of a project, hand-colored blueprints are developed by site personnel to evaluate and explain actual or planned work progress. The chances to identify possible problems and proactively consider alternative workflows are slim, as look-ahead schedules are performed shortly before construction begins.

Planning the work week by week by crew foremen who will actually perform the work is comparable with a more detailed approach (Gil et al. 2000). In two related systems, Last Planner (Ballard 2000) sets a definition for a methodology which generates assignments for look-ahead schedules and weekly work plans, and WorkPlan (Choo 2003) provides detailed descriptions on ways to coordinate these plans among project participants. The links to the master schedule, however, are weak at this level of detail and there is no connection to the geometric model of the project.

2.2.2.4 Linear scheduling models

Linear scheduling or line-of-balance (LOB) techniques are another group of scheduling techniques, mostly used for linear and repetitive activities. The key concerns of these techniques are to make sure that each resource can progress from one activity to the next in an organized manner, and, if necessary, offer continuous utilization of resources. The diagrams for these techniques produce representations of the progress information in a linear style or unit by unit, making them restricted to linear or repetitive tasks in construction projects (Kavanagh 1985; O'Brien 1975; Selinger 1980; Stradal and Cacha 1982).

The above technique was initially developed for industrial production planning used for analyzing the required rate of final products, (Lumsden 1968), It builds up the necessary production rates of all assemblies feeding into the final product, right back to the ordering of materials.

Trades move from one place to another in 3D around installed components in building construction and finish the work that is necessary for the trade that follows. LOB, however, in diagram form, is only able to show limited information. Generally, many extensions are required for these techniques to support construction work (Arditi et al. 2002). Akbas (2004) proposed the process modelling and simulation approach, to aid the general crew workflow representation on geometry, a production rate function bolstering variations in production rates, and detection of interferences between crews to make improvements on LOB methods taking a different path. Using this approach, the differences between these techniques decrease significantly.

Great effort has been made to combine CPM and LOB (Perera 1982; Russell and Wong 1993; Suhail and Neale 1994).

As an extension of LOB means using 3D geometric models, Thabet and Beliveau (1997) provide the details of a planning and scheduling technique based on the usage of spatial areas of activities for multistory building construction. They regard space as a usable resource and describe the space use of each crew over time. They abstract activities into different classes based on space needs and take the workflow direction into account for each crew, as either horizontal or vertical. They break the project geometric models into pieces of structure or grid blocks and analyse each space on an individual basis. The spatial details that drives the scheduling process is the attached space of the grids, instead of components attached in the space. This technique helps in basic spatial analysis.

2.3 Resource Management (RM)

Resource management has becomes one of the many major features of construction planning and scheduling in the current economy. The reason for this is the resource-intensive nature of the construction industry and the fact that the cost of construction resources has risen over the past decades, Resource management techniques are namely resource scheduling, resource levelling and resource allocation. All serve relatively different aims and are applied in the order shown as constraints on project resources before matters such as limited cost and limited construction space become more crucial.

1) **Resource scheduling** plainly provides a profile of resource usage during the period of the project.

2) **Resource allocation** refers to the allocation of resources that are finite. For the sake of eliminating or at least reducing resource conflicts, resource allocation uses the float time of noncritical activities to redistribute the activity start and finish dates. This technique is applied frequently. The project completion date is listed and fixed.

3) **Resource levelling** involves the use of the required resources in an effective manner, when the project duration cannot be modified. Guidelines assign resources to activities based on their criticality levels, with the result that resources allocated to project activities are sensibly limited.

Patrick (2004) discussed, in detail, the aim of the two methods of resource planning. The goal of resource levelling is to reduce the peaks and troughs in a resource profile without the need to increase the length of the project. The technique primarily involves delaying project activities in a time-constrained schedule, the result of which is that the project resources are redistributed. Consequently, resource conflicts are more likely to be eliminated. The objective in resource allocation is to schedule the activities so that resource limitations are not exceeded, while still keeping the project duration to a minimum. The project, therefore, finishes in the shortest period of time possible within the limitations of activity precedence, resource limits, and time constraints, and in that order.

2.3.1 Resource Optimization Methods

2.3.1.1 Traditional resource optimization methods

A number of researchers, have thought of different techniques to handle each feature of resource management. Their methods are grouped into three categories: resource allocation (Talbot and Patterson 1979; Gavish and Pirkul 1991), resource levelling (Easa 1989; Shah et al. 1993), and time-cost trade-off analysis (Liu et al. 1995).

Each classification has a distinct theme and goal. The goal of the time/cost trade-off is to find a time-cost trade-off curve demonstrating the relationship between project length and cost. In general, the aim of the time/cost trade-off analysis is to lower the project cost, without affecting the project duration. The aims of others are described above in the previous section.

These above study types deal with individual features and are, where necessary, applied to projects one after the other, rather than all at the same time. They all have beneficial effects. Because of the fact that the nature of each project is inherently complex and, the difficulties associated with modelling all aspects combined are very great, little effort has been made to realizing combined resource optimization.

2.3.1.2 Mathematical method, heuristic techniques

Resource optimization has been developed based on either mathematical methods or heuristic techniques over the last decades. To solve different resource problems, mathematical methods, including integer, linear, or dynamic programming have been proposed.

Yamin and Harmelink (2001) make a comparison between CPM and the linear scheduling model (LSM) by pointing out the critical attributes of both methods at the project level and also for higher levels of management. As LSM is a tool specially designed for the use of improving linear scheduling by CPM type calculations, it is a better fit for projects with few activities and are to be executed along a linear path/space.

In order to formulate the resource-constrained scheduling problem, Nudtasomboon and Randhawa (1996) developed an integer linear programming model. However, due to the combinatorial explosion phenomenon, the efficiency of that model suffers in large problems. Christofides et al. (1987) and Demeulemeester and Herroelen (1997) developed special algorithms (branch and bound and the implicit enumeration approaches), with the aim of overcoming the combinatorial explosion problem.

In terms of resource-levelling, Karaa and Nasr (1986), Easa (1989), and Harris (1990) presented, for discussion, a number of mathematical programming formulations.

Nevertheless, for real life normal size projects these methods are computationally non-tractable (Moselhi and Lorterapong 1993; Allam 1988). Mathematical models, however, suffer from complexity in their formulation and may be trapped in local optimum (Li and Love 1997; Hegazy 2002).

In order to simultaneously minimize the total cost of the project, Senouci and Adeli (2001) developed a mathematical model for resource scheduling. This model handled resource-constrained scheduling, resource levelling, and project total.

Instead of using rigid mathematical formulations, Heuristic methods, in contrast, use experience and principles with wide applications and researchers have proposed various heuristic methods for resource allocation (e.g. Davis and Patterson 1975; Allam 1988); resources levelling (e.g. Harris 1978); and TCT analysis (e.g. Ahuja et al. 1984).

Boctor (1990) and Padilla and Carr (1991) made an attempt to improve computational efficiency by using heuristic methods. Although the methods produce feasible solutions, they do not necessarily provide suitable solutions.

In spite of their simplicity, heuristic methods have varying degrees of effectiveness depending on the characteristics of the project networks themselves and there are no rigid guidelines that help in selecting the best heuristic method to use. Such models, therefore, cannot guarantee optimum solutions. In addition, the inconsistency of their solutions have contributed to large discrepancies between the resource-constrained capabilities of commercial project management software (Hegazy and El-Zamamzay 1998).

In an attempt to achieve the project aims for optimizing cost, production, or resource utilization, AbouRizk and Shi (1994) used heuristics in a DELAY statistic to make a decision as to whether the number of resources in a simulation model should be increased or decreased. The DELAY statistic is equal to the fraction of time that a resource is idle, relative to its total working time.

For the purpose of handling large, complex systems, Shi and AbouRizk (1995) developed a hybrid simulation and mathematical optimization system. For separate evaluation of each feasible resource state in this model, the large system is broken into smaller sections. The smaller sections are rejoined by mathematical functions while the whole project is optimized mathematically. The method needs significant manipulation by the user to determine the connection types between the smaller simulation model sections, development of the mathematical functions that connect the smaller sections into the entire project, and for the fine-tuning.

2.3.1.3 Simulation Modelling

For the purpose of utilizing construction resources efficiently, computer simulation has been presented in the last thirty years. Although the above mathematical method and heuristic techniques researchers held interest in exploring the practicality of using computer software to illustrate construction processes in reality, practitioners in the building industry may have difficulty in mastering the skills. Developing simulation models as a tool for construction operations, particularly using the cyclone system is a beneficial aid to successful resource planning. Therefore extensive research has been conducted (Halpin 1977). This system has been applied to much design and analysis of construction processes. Various construction simulation tools have been developed based on Discrete event simulation (DES), such as INSIGHT (Paulson 1978), RESQUE (Chang 1987), UMCYCLONE (Ioannou 1989), COOPS (Liu and Ioannou 1994), DISCO (Huang et al. 1994), CIPROS (Tommelein et al. 1994), STROBOSCOPE (Martinez and Ioannou 1994), HSM (Sawhney and AbouRizk 1995), ACPSS (Liu, 1996) and Simphony (Hajjar and AbouRizk 2002). DES has been used as an alternative project planning or scheduling (Carr 1979; Woolery and Crandall 1983; Ahuja and Nandakumar 1985). The use of DES possesses certain advantages over CPM because of its ability to carry out the "what-if" analysis, described above in section 2.2.2.2, to investigate impending and potential problems by taking into account the stochastic and dynamic nature of construction processes. For instance, the tools mentioned above can provide details regarding resource utilization, resource allocation, operation bottlenecks, and productivity rates.

However, not many successful applications of simulation models in construction practice have been found, mostly due to the fact that constructing a model is a complex process and the resulting time required (Shi and AbouRizk 1997). In addition to this: 1) Different kinds of modelling elements are used by many simulation tools, which may make the graphic networks more complex and leads to the result that more time is spent in differentiating the types of activities; 2) Some simulation systems are hard to use because of the requirement of programming, and the obvious time required by users to learn and to become used to the style of the simulation languages; 3) The step of verifying a simulation model and validating the simulation results are crucial. This requires comprehensive skill and experience (AbouRizk et al. 1991), but most systems fail to provide a user-friendly means to realize their purpose. This is especially difficult for most users who do not possess adequate simulation knowledge and experience; 4) Different from CPM, understanding and interpreting statistical simulation results are not easy tasks, especially when the construction system required to be studied is complicated. Each and all of these factors place strong limit on the efficiency of these simulation tools and their applications in the construction industry; and 5) simulation result and process is still not visualized, and in DES, the spatial analysis cannot be executed.

Research with the purpose of addressing the limitations given above has been conducted. Shi (1997, 2001) developed the activity cycle-based modelling

(ACBM) method to translate the activity cycle diagram (ACD) statements of a process into an equivalent executable SLAM II simulation model. By implementing generalized rules into a computer system, the translation can be automated. Instead of building a construction a model that simulates the construction process directly, this approach makes the modelling task into the simpler one of defining an activity cycle diagram, and hence is more easily used.

To perform a scheduling analysis, Zhang et al. (2002a) proposed a combination of the CPM and DES models controlled by an activity scanning (AS) strategy, an activity-based graphical model, an AS-based forward pass, and a backward search algorithm. Compared with CPM and other simulation-based methods for scheduling, the model is able to deal with more complex situations, such as complex logical dependencies between activities, complex and unbalanced resource involvements, and repetitive activity operations. A CPM network has trouble dealing with these situations.

Chua and Li (2002) introduced a resource-interacted simulation (RISim) modelling method that lets site managers develop simulation models, making it possible to naturally understand the problem, rather than through a specific simulation language. Making use of object-oriented modelling concepts, RISim models regard resources as objects and place emphasis on the characterization and interaction of resources. This approach can present a substitute simulation approach that allows site managers who possess enough site process knowledge and little knowledge of simulation to build models on their own.

Lee and Arditi (2006) introduced a stochastic simulation-based scheduling system (S3), which integrates the CPM, the probabilistic program evaluation and review technique (PERT), and the stochastic discrete event simulation (DES) approaches into a single system, able to improve the accuracy of simulation results.

Shi (1999) developed the activity-based construction (ABC) modelling method to be used to simulate construction processes. Unlike other simulation systems for construction operations, such as CYCLONE and STROBOSCOPE, which use various kinds of modelling elements to simulate real systems, the ABC model requires just one type of element, such as the activity, to model construction operations. The graphical model is similar to that of CPM, which appears to be a simple operation and can be handled by construction practitioners without difficulty. One advantage of the ABC modelling over CPM, however, is that it can deal with repetitive operations of activities or repetitive resource utilizations, neither of which is considered by CPM. The ABC method, however, has a few limitations, such as: 1) less visible logical information in the graphic network; 2) unsuitability for complicated construction process scheduling; and 3) the necessity to input information hidden behind each activity. Researchers have also investigated different methods to visualise the DES construction process results based on 2D or 3D models. Ioannou and Martinez (1996) created a text file during simulation to operate 2D visualization software and generate the simulation results using location changes, shape, and colour of icons to represent resources on 2D drawings. Kamat and Martinez (2001) incorporated this idea to 3D visualization tools, generating a text file as an output from STROBOSCOPE to graphically demonstrate construction operations simulated in 3D. Pang et al. (2006) examined the usefulness of Cell-DEVS in sensitivity analysis as affected by different worksite layouts. Wainer and Giambiasi (2002) compared cell-based modelling and Micro-CYCLONE to demonstrate the feasibility of Cell-DEVS. The Cell-DEVS model has been modified and improved by incorporating more complex rules to detect and solve spatial conflicts, and to calculate delays. Zhang et al. (2007) have studied how the Cell-based modelling approach can be utilized in construction simulation. The application of spatial conflict detection in cell-based modeling, which is based on an explicit representation of the worksite, is not available using MicroCYCLONE. Nevertheless, the spatial content in 3D models is not part of the simulation, and the geometric models still need to be manipulated for visualization purposes.

In conclusion, the approaches outlined above all possess the following limitations follows: 1) Spatial analysis of the construction process needs to be executed; 2) Resource allocation or levelling is little analysed; 3) The construction schedule cannot be automatically generated; and 4) Optimization methods are little applied to the simulation. In an attempt to eliminate these drawbacks, visualization methods and optimization methods should be introduced into simulation-based planning methods.

2.3.1.4 Priority Rule Scheduling and Neural Network

Kolisch (1996) has investigated priority rule scheduling in great detail. A priority rule schedule has two components, a priority rule and a scheduling scheme. By building on to a part schedule, the scheduling scheme is constructed in stage wise fashion. In order to achieve the shortest possible project length, the priority rule predicts, among the eligible tasks, which task should be scheduled at the present point in time. Priority rules include greatest rank positional weight and least slack.

A priority-rule-based heuristic for use in the construction industry was developed by Lu and Li (2003). Time and resource needs of a task are considered in deciding priority and work-content determines the priority. They show that their priority rule is competitive with other priority rules.

Lu and Li (2003) explored a resource-activity critical-path method (RACPM), allowing that 1) in project scheduling, the dimension of resources as well as activity and time, is emphasized to make activity planning and resource planning take place at the same time smoothly; 2) with reference to resource-technology integrated precedence relationships, the start/finish times and the floats are described as resource-activity features; and 3) the crucial issue of resource, such as a worker or a piece of equipment, which had baffled the construction industry for a long time was explained.

Golenko-Ginzburg and Gonik (1998) worked on developing a decision-making process to decide the time at which each task is to start and what resources should be utilized at the beginning of a project. Nozick et al. (2004) present the notion of resource multipliers which determine the quantity of a resource to be distributed to a task. As the resource multiplier changes, the probability distribution for the duration of the task is modified accordingly. In an attempt to optimize resource allocation policies, Vaziri et al. (2005) make use of the notion of resource multipliers and build a heuristic that combines simulated annealing with a parallel scheduling scheme. Their general model and solution procedure was substantially modified by the author to suit the special characteristics of the construction industry.

With the use of an augmented Lagrangian multiplier and a discrete-time Hopfield net, Savian et al. (1996, 1998) presented a neural network application for construction resource levelling. The formulation objective was to make the resource requirements as uniform as possible. Nevertheless, several important factors such as the case of non-uniform resource usage, failure to perform cost optimization and the rejection of more than one type of precedence relationship (finish-start) or more than one resource type, were not allowed for by the formulation.

2.3.2 Innovative Resource Optimization Methods

As computer technologies advance, tools that are favourable to the applications of construction have been mushrooming in the market. According to recent advances in artificial intelligence, a new optimization technique, using genetic algorithms (GAs), has been developed.

In the 1970s, John Holland conceptualized the genetic algorithm, which was devised as an algorithm for optimization in the first place and for numerical simulation of the process of evolution. Following the rule of “the survival of the fittest”, the essence of the algorithm is developed to achieve possible solutions, i.e., the chromosomes (which is an organized structure of DNA and protein found in cells. It is a single piece of coiled DNA containing many genes, regulatory elements and other nucleotide sequences.) compete among themselves, replicate, mate or crossover, mutate, are evaluated in terms of an objective function, and further evolve based on the evaluation result. In order to survive and further evolve better, higher fitness of the chromosome is generated.

2.3.2.1 Genetic algorithms (GAs)

Applying the renowned natural-evolution and survival-of-the-fittest mechanisms, GAs perform a random search for the optimum solution to a specific problem. With their perceived benefits, GAs have been used to solve several engineering and construction management problems with huge success.

GAs were also used by Chan et al. (1996) and Hegazy (1999) to strive for optimization of resource allocation and levelling concurrently and therefore achieved a shorter project period and a better-levelled resource profile.

With reference to a genetic algorithm, Chan et al. (1996) proposed a resource levelling method based on a genetic algorithm. Even though the method was applied to both resource-constrained scheduling and project duration minimization, it did not succeed in minimizing construction cost, only allowing finish-start relationships, and permitting only one resource type. The concept of current float was used in the string representation of GAs to set the scheduling priority.

An optimization model with the use of heuristic methods and genetic algorithms was introduced by Hegazy (1999), a method seeking to find near-optimum solutions and examining both resource allocation and resource levelling concurrently. Nevertheless, minimization of project cost was not included and optimum solutions were not generated by the project. In the integrated model, though many constructive improvements were made, it is a must that a time-cost trade-off analysis should be combined into the GA procedure. The convenient employment of GA in business project management software systems is a significant benefit of the technique.

In addition to resource allocation, other models making use of GAs put emphasis on time/cost tradeoff analysis. Feng et al. (1997) identified the pareto front in the project time-cost tradeoff analysis. With an attempt to minimize computational costs and enhance the efficiency in searching for optimal solutions, Li and Love (1997) suggested a number of improvements based on GAs into time-cost optimization problems in construction planning.

Leu and Yang (1999a) introduced a computational optimal scheduling model with a set of criteria that integrated a time-cost trade-off model, resource-limited model, and a resource-levelling model for construction scheduling use. Using the method, the solutions created were suboptimal since the cost was not pursued to the minimum. As reported by the researchers, resource clashes were detected; therefore, resource levelling should still be improved.

In order to seamlessly combine allocation of limited multitasking resources into resource-constrained CPM scheduling, the GA-RACPM (Genetic Algorithm enhanced Resource Activity Critical Path Method) software was developed (Lu and Li 2003). The GA-RACPM software was employed in developing resource-constrained scheduling analysis by adjusting the priority values for activities so as to allocate multiple available resources to different activities to minimize the total project duration.

To solve nonlinear time/cost tradeoff problems, Senouci and Eldin (2004) suggested the used of a hybrid GA model which allows any linear or nonlinear function for the representation of cost-duration and resource-duration relationships. One drawback is that it failed to take into account the effect of various combinations of resource limits.

According to the above details, the suggested optimization models mainly considered deterministic problems. As mentioned above, for several GA-optimization models, a common problem is that the input parameters (activity durations and costs) are plainly represented with deterministic values rather than statistical distributions. In addition, with reference to the literature, only a few developed probabilistic models that consider resource constraints have been proposed.

In order to fulfill the aim of accommodating the uncertainties of activity duration and minimizing the project duration, Leu et al. (1999) further incorporated the fuzzy set theory into a GA-based resource-scheduling model. Though a GA-based approach was utilized to look for optimal fuzzy profiles of project duration and resource amounts limiting with the constraint of limited resources, the method failed to achieve project total cost minimization.

Leu and Hung (2002) introduced an approach, with the use of the GA and Monte Carlo simulation, to develop a resource-constrained scheduling model under uncertainty. Feng et al. (2000) developed a hybrid technique that integrated simulation techniques and GAs to solve the time-cost trade-off problem under uncertainty. The approaches they provided are useful solutions for project scheduling under uncertainty, but they failed to take different combinations of resource limits in the optimization process or attempt to seek the optimal combination of resources.

Cheng and Feng (2003) combined genetic algorithms (GAs) and simulation to efficiently find the optimal resource combinations based on different objectives, such as minimizing unit cost or maximizing productivity rate in the simulation model. Hegazy and Kassab (2003) integrated a flowchart based simulation tool using the GA technique for resource optimization.

Instead of utilizing GA alone, Cheng et al. (2005) made use of a Heuristic algorithm (HA) and GA together to improve the efficiency of locating the optimal resource combination.

2.3.2.2 Others

Hegazy and Wassef (2001) proposed a practical model for the scheduling and cost optimization of repetitive projects. The model objective was to minimize total construction costs, comprising direct cost, indirect cost, interruption cost, as well as incentives and liquidated damages. The novelty of this model stems from four main aspects: 1) it is based on full integration of the critical path and the line of balance methodologies, thus considering crew synchronization and work continuity among non-serial activities; 2) it performs time-cost trade-off analysis for a specified deadline and alternative construction methods with associated time, cost, and crew options; 3) it is developed as a spreadsheet template that is transparent and easy to use; and 4) it utilizes a nontraditional optimization technique, genetic algorithms, to determine the optimum combination of construction methods, number of crews, and interruptions for each repetitive activity.

Zhang and Li (2004) developed an optimization methodology, which integrates discrete-event simulation (DES) with a heuristic algorithm, to optimize dynamic resource allocation for construction scheduling. This heuristic algorithm was based on the objective of minimizing project duration and will consider activating multiple activities at the same time based on limited quantities of resources. The optimization was implemented through DES, which could describe complex operational systems through simulation models, without the need to build mathematical models. The proposed methodology provided an alternative to optimizing resource flow for scheduling and broadens the application potential of discrete-event simulation in the construction field.

Li (1998) proposed an application of Petri nets in assisting the framework of process improvement in the construction industry. He described how Petri nets could be used to describe the workflow of a re-designed process, and demonstrated how to identify and select which aspects of the workflow to re-design. After the process was re-designed, the Petri net was used again to evaluate and verify the performance of the new process.

Reyck and Herroelen (1999) presented a local search-based solution methodology, which was able to handle many real-life project scheduling characteristics such as time-varying resource requirements and availabilities, activity ready times, due dates and deadlines, activity overlaps, activity start time constraints and other types of temporal constraints.

Tompkins and Azadivar (1995) combined genetic algorithms with object-oriented programming in ModSim II to develop a means of optimizing simulation models for manufacturing systems. The system is intended to represent corporate policy for minimizing resource requirements of new operations. Several billion points can be searched resulting in significantly improved solutions over random search methods.

Zhang et al. (2006a) proposed an alternative heuristic method for scheduling repetitive projects, in which resources were limited and activities might be executed with multiple modes of resource demands associated with different durations. Unlike general heuristic methods that separately analyse each competing activity and schedule only one at a time, the proposed heuristic algorithm ranks possible combinations of activities each time and simultaneously schedules all activities in the selected combination leading to minimal project duration. All alternative combinations of activities in consideration of resource constraints, multiple modes and characteristics of the repetitive projects are determined through a permutation tree-based procedure. The heuristic method is implemented based on the corresponding framework.

However, research presented on these topic is based on a single objective. Also, the research does not provide a method of obtaining near-optimal solutions within a reasonable amount of time, which is the main disadvantage of GAs.

2.4 4D CAD

Illustrating data and concepts through graphics is called visualization which is a realistic depiction of information generated by an analytic model, leaving the users to make their own interpretations and to detect patterns (Ware 2000). With reference to the requirements of construction processes and the advances in digital technologies, research into the development of visualization-based modelling of the planning process has been increasing.

As a common practice in the construction industry, different participants create both construction schedules and drawings of the items to be built separately. Construction schedules mainly provide information on timings and activity relationships, and drawings are prepared in two dimensions generally. This graphical information about construction components and the overall timings of the construction activities provide the two information sources that construction teams utilize to understand and execute their work. Nevertheless, good understanding depends on individuals interpreting the documents identically, a situation which cannot be relied upon. Usually, different people interpret differently to some extent, leading to misunderstandings which can result in collaboration problems and conflicts in the sharing of resources. As a solution the 4D CAD model combines the two separate information sources, helping create explicit visual perceptions. Therefore, adoption of 4D CAD can be an effective means of promoting collaboration among construction teams.

Improvements in three-dimensional (3D) computer-aided design (CAD) technologies in the past twenty years have provided the opportunity for enterprises to apply 3D models to handle project construction information, by viewing static realistic images. However, these 3D models by themselves lack the ability to show the exact status of a project at a designated time, and furnish little assistance to progress control. Data integration and interaction between the 3D model, schedule information and other data is absent. For the purpose of producing a construction schedule from 3D drawings, planners have to envision the order of construction processes in their mind which is not an easy task due to the fact that workspace logistics and the utilization of resources, including plant are dynamic and clashes for space, for example are sometimes hard to envisage. Sometimes works planned based on the initial site layout and resource utilization diagrams are seldom updated during the project duration. Therefore, in real terms, site managers have not gained much benefit from recent improvements in computer technology.

The 4D (3D plus time) is a geometry-based construction process visualization tool which integrates the 3D model with time. The fundamental aim of the technique is to create a time-lapse visualization of a construction process by associate components and CPM schedule activities (Koo and Fischer 2000). The 4D technique visually represents the installation states (the start and finish dates of activities) on the 3D geometry of the finalized facility through colour-coding. 4D models use a discrete-time scale. Visualization of the future project status is available over a series of preset discrete times.

Using the procedures in Figure 2.2, 4D CAD can be developed (Benjaoran and Bhokha 2009):

1) prepare 3D CAD model from the 2D CAD drawings;

2) arrange a construction schedule;

3) link 3D CAD objects with construction activities through linking keys (e.g. activity name; layer); and

4) create a simulation control and a visualization

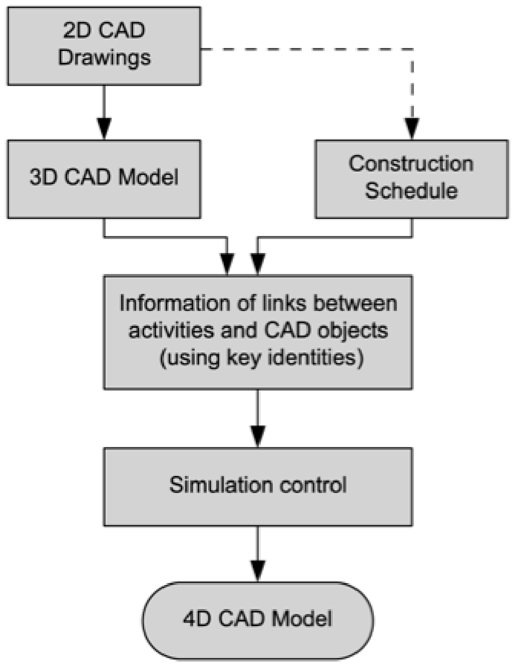


Figure 2.2 The development procedure of the 4D CAD model (Benjaoran and Bhokha 2009)

A number of research studies have focused on generating advanced four-dimensional (4D) planning models by integrating three-dimensional (3D) visualization with the time factor. Heesom and Mahdjoubi (2004) analysed the research about 4D planning and subsequently classified the research into the three categories of 1) product modelling and visualization; 2) process modelling and analysis; and 3) collaboration and communication.

2.4.1 Production Modelling and Visualization

The common tool of visualization of the construction schedule is 4D, which is a three dimensional (3D) model combined with time/schedule, to enable planners to visualize the construction sequence.

Adjei-Kumi and Retik (1997) applied the concept of virtual reality to visualize construction plans using a library-based 4D model. Similarly, McKinney and Fischer (1998) have developed 4D tools for generating, evaluating and visualizing construction schedules with CAD. This has arisen because of software technology advances enabling the linking of 3D CAD objects and the construction activities information during the model development procedure. 3D CAD objects can be chosen by hand to relate to activities in a construction schedule through the medium of dialogue boxes.

Koo and Fischer (2000) applied 4D CAD in commercial building construction in order to minimize the limitations of the traditional CPM and bar chart analysis. They concluded that a tool for facilitating the understanding of construction work was possible. It helps with the detection of errors, omissions, or inconsistencies in construction plans, and is useful for evaluating the constructability of the designed sequences. On the other hand, it also examines the degrees of congestion and accessibility of working space. Due to the fact that construction activity schedules use textual names and duration bars, such problems are not evident from a Gantt chart.

Dawood et al. (2003) have developed an integrated database to act as an information resource base for 4D/VR construction process simulation and validated it on building projects. A Standard Classification Method (Uniclass) was employed to design the database. As for other means, proper 3D CAD objects are categorized into different layers or blocks which are then automatically matched with the appropriate activities in a construction schedule using rule-based programming.

Likewise, Wang et al. (2004) developed a 4D Management for Construction Planning and Resource Utilization (4D-MCPRU) system which links a 3D geometrical model with resources to obtain the necessary resource requirements. A work breakdown structure template is employed to link with 3D CAD objects while their 4D CAD model originated a two-way data exchange mechanism with the schedule. An interactive linking means connects together the functions modeling the 3D CAD objects and compiles a construction schedule.

In addition, Russell et al. (2009) use linear scheduling (i.e. LOB) and 4D CAD to visualize high-rise building construction. Sampaio and Santos (2011) used a virtual reality connected construction schedule to allow the visualisation of different stages of construction.

2.4.2 Process Modelling and Analysis

2.4.2.1 Process modelling

One of the main advantages of 4D CAD for process modelling is the ability to analyse various construction schedules and assess their logic. Songer (1997) highlighted the advantages of such simulations for analysing schedule logic. Additionally, work undertaken by Koo et al. (1998) demonstrated that 4D could assist the identification of problems that would normally be overlooked in traditional schedule representations, such as bar charts and network formats. Using 4D technology allowed relatively inexperienced construction professionals to identify problems that might be overlooked even by experienced personnel in the traditional schedule formats. This analytical capability has been further exploited by allowing construction-planning students to visualize and analyse a complete construction schedule prior to construction to assess the suitability of a construction plan (Koo and Fischer 2000; Jaafari et al. 2001).

2.4.2.2 Analysis

New types of analysis become possible. The 4D CAD model is a tool with great potentials for analyses and decision support in aspects including time wastage, working space, sequences, and temporary structures. Visualizing virtual construction scenes lets practitioners be alert and foresee any errors or schedule unsuitabilities.

Chau et al. (2005) utilized these techniques for construction site and resources management. Ma et al. (2005) employed it for planning site layouts at different construction stages. In order to better the work-flow of construction activities, Jongeling and Olofsson (2007) presented a location-based schedule method which can be enhanced with the 4D CAD model. Ma et al. (2005), and Chau et al. (2005) made use of 4D models in the site planning and management of construction projects. Collier and Fischer (1996) showed visual-based 4D modelling and scheduling via the real-life example of the San Mateo County Hospital. McKinney et al. (1998) illustrated the capability of 4D-CAD models to detect construction problems before they actually occurred. Retik et al. (1990) examined the feasibility of using computer graphics in conjunction with construction scheduling and researched the functions needed. In terms of simulation, visualization, and communication, Williams (1996) designed a 4D model based on demands for the generation of a graphical construction. Liston et al. (1998) explored a 4D-CAD visual decision support tool for construction planners, with visual cues for depicting problem areas in an efficient manner. Staub-French et al. (1999) demonstrated that 4D simulation was a more effective tool for construction planning than Gantt charts or CPM schedules.

Another important use of 4D is to analyse spatial conflicts. Akinci and Fischer (1998), for example, use a 4D model to perform and analyse these time–space conflicts, while Akinci et al. (2002) developed their 4D WorkPlanner Space Generator (4D Space-Gen) to generate project-specific work spaces from a generic work space ontology and a project-specific IFC (industry foundation class) based 4D model. Winch and North (2006) proposed the idea of critical space analysis and used the 4D CAD model as a means. The advances can optimize space distributed to tasks taking account of the critical path schedule. As a result, hazardous spaces which may arise due to certain activities can be studied with the use of a 4D CAD model. Dawood et al. (2005) explored a strategic decision support system (VIRCON) for managing construction schedules, especially space planning. The VIRCON system enables planners to exchange the task time sequences in harmony with their spatial representation distribution, which leads to a more robust and rehearsed project schedule. Dawood and Mallasi (2006) also use 4D visualization to resolve conflicts between work-face construction activities, and Tantisevi and Akinci (2009) present an approach to automatically simulate the motion of mobile cranes for collision detection, with a recent contribution from Lai and Kang (2009) involving the development of a collision detection algorithm for virtual construction simulation. Haque and Rahman (2009) developed a 4D model. The model incorporated spatial requirements along a chronological schedule of events. It was applied on construction sites with the aim of detecting conflicts existing as regards activities, time schedules and construction space requirements.

In addition, the 4D CAD model has been employed in connection with construction safety. Rozenfeld et al. (2009) explored a method known as CHASTE (Construction Hazard Assessment with Spatial and Temporal Exposure), which provides an automatic detailing of loss-of-control scenarios using the CJSA knowledge platform, computation of exposures through connection to a 4D model of the construction procedures, and measurement of risk levels combining severity levels for each loss-of-control scenario, to carry out safety risks analyses of dynamic individual site operations. Hu et al. (2008) introduce analytical procedures based on 4D technology and BIM to show possible safety threats during a continuous and dynamic simulation of the whole construction process. Chantawit et al. (2005) have begun to use a 4D CAD model to help the process of identifying hazards. A safety library, which stores records of predefined safety measures collected from regulatory standard and safety engineers' experience has been established. It enables the planning and integration of safety and health requirement enabling decisions on suitable safety measures for the project progress concerned. Benjaoran and Bhokha (2010) developed an integrated system for safety and construction management using the 4D CAD model. The rule-based system is the core of the integrated system and is used to analyse the combined information to automatically detect any working-at-height hazards. It also indicates necessary safety measures in terms of activities and requirements. These safety measures are inserted into the construction schedule and visualized using on the 4D CAD together with the other construction sequences. Zhang et al. (2012) developed an automated safety-checking platform to analyse a 4D model to also detect safety hazards. However, the platform is able to suggest preventive measures to users for different cases involving fall related hazards.

The combined design, cost, and schedule model stores progress information and reports the construction process status (Fischer et al. 1999). In order to help with cost control and estimating, 4D visualization technology has been utilized. Tanyer and Aouad (2005) incorporated project cost aspects into a 4D model to make available an nD model. Staub et al. (1998) pointed out that 4D simulations can be connected with cost estimating software tools for the use of automated quantity takeoff. This work identified the benefits and shortcomings of commercial software tools available for help with combined design-cost-schedule management from initial design to construction, in a multi-company environment. The project concluded that knowledge of the relationships between design, cost and schedule information, construction planners and managers can easily disseminate design and planning changes, whilst making sure that project design, cost estimate, and construction schedule fit well together. Extra work has connecting 4D information to the cost schedules automates the production of cost breakdowns. As an example, O'Brien (2000) proposed that '5D CAD' should take the cost aspect of the construction process into account. Fischer (2001) emphasized that the cost benefit analysis of using 4D models in both the construction planning and control phase. Terashma et al. (2011) developed a system, which integrates different kinds of data and enables the simulation of the construction progress by gradually illustrating 3D models with reference to the activity schedule. Materials data are attached to each 3D object with the objective of displaying related information such as cost and even object properties. The requirement assumptions of this system are: (1) to import and display the 3D modeling data, (2) to import the project schedule, (3) to link each model and activity, (4) to give the materials data of each object to enhance reality, and (5) to show cost accumulation.

With an aim of advancing the analytical ability of 4D CAD, simulations are being connected to other tools utilized by the construction industry. Moore (2002) put forth the application of 4D technology within the field of Geographical Information Systems (GIS). This work demonstrated a real-life example of the use of GIS in the design of a stadium facility, letting topological queries to be related to timing aspects.

2.4.3 Collaboration and Communication

Allowing 4D simulations produce and visualization in a collaborative environment will help construction process collaboration. With reference to the fragmented nature of the construction industry (Issa 1999), many different contractors and subcontractors can be performing tasks on the one construction site throughout the different stages. Therefore, making use of a 4D model can facilitate the communication between individual contractors to best decide when each task should be done and prevent the occurrence of conflicts between trades. Making use of 4D CAD for collaboration and communication has attracted the attention of many different parties. The practice of project planning today, was described by McKinney and Fischer (1998) as making use of a "mental 4D model", which pointed out the existence of a mental relationship between the 3D building products and the schedule of activities. The use of mental 4D models causes ambiguities between visualised representations of the construction project by different people and can cause communication and collaboration problems between the client, the contractor and sub-contractors. An individual party receives project information such as a project schedule, 2D drawings and a 3D product model and based on this, forms a mental 4D model, of how the building will be built. However, individual mental models are always different from each other, which leads to communication difficulties. A real 4D model obviates these differences and as a result all parties can understand the process well and communicate with others using the same model. The Centre for Integrated Facilities Engineering (CIFE) at Stanford University and Walt Disney Imagineering (Haymaker and Fisher 2001) used 4D to help with collaboration. In addition, that research group made use of the 4D tool on the Disney Concert Hall in Los Angeles, designed by Frank Gehry to assist in co-coordinating subcontractors, examining the constructability of the design, and confirming the robustness of the construction schedule (Goldstein 2001).

In order to help with the design process, McKinney et al. (1996) introduced a four dimensional computer-aided design (4D-CAD) tool with visual and communicative functions. To better the communication between the contractor's site management staff and the labourers, Mourgues et al. (2007) utilized 3D and 4D models on the jobsite reduce communication difficulties by supporting the delivery of accurate, precise, and useful work instructions. Hartmann and Fischer (2007) developed a combined process enabling project teams to make use of 3D/4D models in a timely manner to help with the knowledge communication and generation needed during the constructability reviews. A Four-Dimensional (4D) Site Management Model 4DSMM was explored by Chau et al. (2005) to simulate the state of a site at any date specified by the users so as to engender good communication of site use intentions among site practitioners.

2.4.4 Commercial 4D Software

2.4.4.1 Tekla Structures

As a structural engineering software system for creating and managing all types of 3D structural models made of steel, concrete or any other materials, the function of Tekla Structures includes design coordination, production planning and procurement. An integrated model solution facilitates progress from engineering design to product manufacturing. A 4D function meanwhile updates geometry and schedule dynamically and enables virtual construction simulation of work-flow and assembly order according to schedule. (Tekla ed. 2011)

2.4.4.2 Navisworks

For the sake of enhancing collaboration possibilities, Navisworks provides the platform for combining different discipline project models including architectural model, structural model, building services model, for interference management and clash detection. Therefore, Navisworks is compatible with most major 3D design and laser scan formats. Microsoft Project or Primavera schedules are two kinds of software that the 4D simulation can link to in order to develop construction sequences and to check clashes and time and space co-ordination. (Autodesk ed. 2011)

2.4.4.3 FourDviz – Balfour Technologies

Using FourDviz, a virtual scene can be formed by generating virtual reality objects thereby creating a real time environment for the user to navigate, allowing movement through any part of the virtual construction site. Apart from creating 3D versions of the objects, timing information can also be attributed. As soon as a date is attributed manually to an individual object in the 3D world, a simulation is compiled for the length of a specified period. The temporal characteristics of 3D objects are assigned as particular dates or days, and as such, no analysis is made of the schedule compiled. Due to the fact that FourDviz lacks a scheduling engine or the ability to perform a critical path analysis, the calculation has to be carried out before dates are associated to objects. Furthermore, there are no dynamic links between a CPM based package and the visualization.

2.4.4.4 Common point 4D

Common Point 4D is a 4D CAD tool which includes some specialized 4D features such as construction sequencing, plant movements and site management features, visual comparisons on status and planned progress, and communication of a model analysis to stakeholders. This is a product arising from the research at Stanford University, USA. Drag-drop manual linking and automatic linking are two components in the 4D linking process. The time scale can be modified and the annotations or comments can be added into the 4D simulation. For the purpose of offering alternative scenarios, tasks can be edited in the 4D software.

2.4.4.5 ConstructSim

ConstructSim was established for factory plant projects. By closing gaps between design, construction, and operations, the integration of Common Point's technology with Bentley's ProjectWise Navigator platform and comprehensive portfolio of applications and collaboration servers are able to help Bentley to accelerate integrated project delivery for infrastructure projects. On account of the planning, sequencing, execution and monitoring of construction activities, ConstructSim V8*i* can improve utilising a data rich virtual plant model. (Bentley ed. 2011)

2.4.4.6 Vico Virtual Construction

Vico Virtual Construction makes the 3D virtual construction model estimating and scheduling data consistent and helps construction companies determine the best way to construct buildings. Project constructability, estimating, cost management, schedule planning, procurement, and change management processes are included in the Virtual Construction suite. (Vico ed. 2011)

2.4.4.7 Innovaya Visual 4D Simulation

Innovaya Visual Simulation links Building Information Models (BIM) objects with scheduling activities. The tool also conducts 4D construction planning and constructability analysis and it helps to optimize project communication, coordination, and construction logistics planning. The 4D Simulation technology possesses a powerful 3D engine and a user-friendly interface which can help build optimized task sequences, save project time and play what-if scenarios with traditional GANTT chart schedules. (Innovaya ed. 2011)

2.4.5 The Limitation of 4D CAD

Other than the advantages of 4D, which have been highlighted the technique also possesses shortcomings.

Instead of being used as a tool for analyzing the construction process, most 4D models are generally utilized by clients for visualization and demonstration purposes. Users can make use of the 4D CAD tools to connect a 3D model with a construction schedule and as a result visualize construction completed over time on a computer screen and the users can also question the content and relationships between the objects concerned. Nonetheless, the finished 4D model is just a visualization tool, but not a tool that can be used for performing analysis (Heesom and Mahdjoubi 2004). Currently, 4D CAD models are being used for planning, design phase analysis, and postmortem or appraisal types of analysis, but only a few of them have been used in practice as tools for construction phase decision making and administration (Martinez and Halpin 1999). Fischer (2001) proposed that the level of detail of the visualization affects the level of detail of the construction schedule made by the planner, which therefore relates to the degree to which the product is decomposed in the 3D model.

Another aspect of 4D CAD that affects software systems is the common focus on aesthetic visualization of construction progress with less advanced choices for the analysis of scheduling scenarios (Heesom and Mahdjoubi 2004).

Furthermore, if 4D CAD models are constructed on one broad level of details collaboration between general contractors and subcontractors is not helped. Both will try to complete the common objective, but inevitably they will have different mental models and at various levels of details due to contractors' focus on management and the monitoring of the sub-contractors' work. The sub-contractors traditionally are not in favor of monitoring activities. Their objective is to complete construction as speedily as possible, often with less care to safety practices. The latter is not acceptable to the contractors and as unsafe practices become evident when presented in 4D, the latter is not favoured by the sub-contractors. Apart from that, major 4D CAD applications do not support computer-based analyses of cost, safety, and other performance metrics (Heesom and Mahdjoubi 2004). 4D models fail to show every piece of information, such as the resources and materials, needed to assess the construction schedule. 4D models are generally more useful at the overall project level than at the site operational level (Huang 2008). A major reason for this is that the model is built upon the CPM method and 3D geometrical inputs. This means, it possesses some of the limitations of the CPM. For instance, it makes the assumption of a constant production rate for the period of an activity, and it fails to capture or visualize the reasons behind the given plan or any geometric planning parameters (for example, workflow directions). What is more to match the geometric representation with the process description, manipulation of geometry inputs and scheduled activities is needed, and associations with finishing elements. The process needs a lot of time investment, trials and errors while no explicit use of construction process information for geometric and activity manipulation occurs. Whenever a single change is made to a plan, the 4D model needs manual updates. Consequently, it is not realistic to test many alternatives with such 4D models.

Until now, most of the methods used for optimizing planning have been investigated. All the methods have advantages and disadvantages, but no existing method comprehensively considers resource allocation as well as planning and scheduling. The comprehensive consideration of resources should include use of space, tower crane, crew etc.

2.5 Resources Requiring Analysis in Construction Planning

AbouRizk et al. (2010) stated that resources include space, crews and equipment. However, Liu and Ioannou (1992) stated that time and materials were also resources. Time is related to all other resources in some way, of course. Materials are resources, which link to storage and logistics activities, i.e. activities that support construction but are not product construction activities directly.

2.5.1 Tower Crane

On construction sites, the tower crane is one of the most commonly utilized and shared items of plant involved in many different construction tasks. For instance, when constructing steel or precast reinforced concrete buildings, the tower crane is used for structural member erection, lifting precast facade elements and curtain wall systems, hoisting skips of concrete, as well as a number of other materials and nonstructural items. Due to the fact that many construction activities often need the tower crane efficient allocation of its time has considerable positive effects on the overall schedule, cost and safety of a construction project (Kang and Miranda 2006). For high-rise construction, the tower crane is especially important to the overall construction schedule. Leung et al. (2001) believes that the allocation of cranes to different trades such as concreting, installing precast concrete units and fixing formwork panels is a crucially important resource planning issue.

2.5.2 Space

Crews will interfere with each others work if they share space. One particular crew would not able to proceed in a timely manner until the other finishes and moves to another spot. For this reason, modelling the direction of workflow for construction crews is fundamental to site planning. However, CPM fails to capture space needs information (Birrell 1980). Linear scheduling methods do conceptualize space occupied as crews move in a fixed direction such as horizontally to the north, vertically upwards. Research, such as Thabet and Beliveau (1997) also models the use of space in a fixed linear direction. Riley and Sanvido (1995) summarize the work-space planning literature into the three categories of site-layout method, spatial traits of construction work, and ways to quantify space need. Akinci et al. (2002) use a computer to decide the micro-space requirements of activities with reference to the construction method and component geometry. They also analyse time-space clashes using this model, assuming that the work locations are correctly defined at the micro level.

2.5.3 Crew

The crews as the processing units produce the finished geometrical constructed items. Various factors including shape effects and resource availability are taken into account during the production process. A number of past efforts included calculation factors on productivity rates. In construction, estimating productivity rates mainly applies at the activity level and impacts on productivity rate are special factors.. Some research has been done to determine geometric factor effects on labour productivity rates (Sanders and Thomas 1991; Thomas et al. 1990; Thomas and Zavrski 1999). These studies discovered that certain design features can impact on the productivity rate, e.g. masonry walls with corners that are not perpendicular, and have assigned a factor (called *work content*) to define the effects of shape on productivity rate. Nonetheless, these research efforts fail to consider shape variations within a component; instead setting a bulk factor for the whole element. Other researchers use a linear combination of different factors to model impacts on the productivity rate. For instance, O'Brien (1998) takes modifiers into account when there are shared site resources, such as access routes, for site clean-up work and shared areas availability.

2.6 Building Information Modelling

The concept of Building Information Modelling (BIM) has been in development for over three decades (Eastman et al. 2008) and was developed because of the need to have a digital simulation of the building process. The National Building Information Model Standard (NBIMS 2006) defines BIM as "a digital representation of the physical and functional characteristics of a facility and serves as a shared resource for information about a facility and forms a reliable basis for decisions during its lifecycle from inception onward and then also refers broadly to the creation and use of digital models and related collaborative processes between companies to leverage the value of the models." For the time being, BIM is recognized by many as a tool, process and/or product which is utilized to explore virtual intelligent models connected to other construction management tools (i.e. scheduling, estimating) that help with collaboration, visualization and constructability reviews benefiting all stakeholders throughout the lifecycle of the facility (Kymmell 2008). BIM models are object-based parametric models with a predefined set of object families, each having behaviour programmed within them. These new functions let organizations define object families based on their own needs and to support their own means of detailing and layout. The idea of BIM has also been used by most of the commercial CAD software systems, such as Autodesk Revit Series, Bentley Architecture's interface, GraphiSoft ArchiCAD, etc.

Campbell (2007) demonstrated the different creative methods that designers and contractors were using via BIM and Web3D tools in the building industry which are 1) design visualization; 2) design assistance & constructability review; 3) site planning and site utilization; 4) 4D scheduling and sequencing; 5) cost estimating; 6) integration of subcontractor and supplier models; 7) system coordination; 8) layout and fieldwork; 9) prefabrication; 10) operations and maintenance. The 4D model is generated by using both the BIM model and construction schedule with time as the fourth dimension to provide the base for schedule visualization and sequencing optimization on the construction site. In most cases, craft-workers who find it hard to understand traditional drawings and schedules have no difficulties in understanding and participating in project scheduling when the BIM supports 4D.

Zhang and Hu (2010) propose a 4D structural information model into a combined solution of analysis and management for conflict and structural safety problems in the course of construction, by making use of BIM and 4D technology. Four types of applications are listed as follows: 1) 4D structural safety analysis: Time-dependent structural models and the corresponding unit types, loads, material properties, boundary conditions, etc., can be generated based on the information model at any user-specified time point; 2) 4D schedule conflict management: At any user-specified time point, schedule conflict analysis can be carried out according to the plan schedule, actual schedule, milestones, critical path, and priorities; 3) 4D resource and cost conflict management: Resource demand and the total resource amount can be determined by the information model for resource conflict analysis; 4) 4D site conflict management: According to the space–time information, conflicts among site entities and time-dependent structure components can be determined by applying a collision detection algorithm.

Zhang and Li (2010) developed a 4D Virtual Construction and Dynamic Management System in terms of BIM to overcome the “information gap” and the “information silo” limitation and visualize the construction process interactively on a flexible planning timescale to realize dynamic construction management.

Some of the research presents ways to create time schedules and 4D visualizations with reference to the data recorded in the BIM model.

Tulke and Hanff (2007) introduced a method to prepare 4D construction process simulations by utilizing 3D models as well as a BIM database accessed through Standard Query Language (SQL). As reported in the study, less time and effort is used to prepare a 4D simulation. The authors pointed out that improvement is a must with visualization, such as more support for scaling and moving construction components or equipment and such as simulation of processes inside a building.

Staub-French et al. (2008) looked into the automatic connection between the product and the process model. Moreover, the link acts as a class definition, i.e., as a definition of styles within the CAD application, instead of a definition of instances. It empowers a generalized application of CPM that includes linear scheduling related with a BIM model to generate 4D CAD pictures.

As an excellent technique for data management, the BIM is useful for retrieving information and displaying a format in line with either the constructor or owner’s requirements. The owner can opt to arrange the data by rooms or systems in a more efficient availability manner. BIM can obtain this information by any parameter organized by the user (Goedert and Meadati 2008). The use of BIM helps with trade coordination due to the fact that it turns architectural and engineering design and management disciplines of cost estimating, time scheduling, constructability analysis, risk management, procurement, etc. into parallel and combined processes (Kousheshi and Westergren 2008). Even though the benefits of the BIM have been carefully recorded and realised by many architects and consultants performing tasks in the early stage of construction, the use of BIM for the management of construction work, e.g. scheduling, is, nevertheless, still yet to happen in industry (Goedert and Meadati 2008). The data management ability of BIM is its limitation. BIM was designed for companies that utilize individual safety databases because companies that design BIM software have their own data management formats. When a user utilizes BIM software to generate a 3D model into a 4D model, certain information is added to the 3D model, the format of this information could cause clashes resulting in potential errors. There is not a wide application for open data-sources and data management in BIM. Regarding the 3D-based BIM object information system, BIM can be used to convert a 3D model into a 4D model. The 3D graphical model as well as the project file are both full of information and potential errors could happen in hardware and software because of for instance, not enough memory, program clashes, or software bugs which can occur in relation to 3D graphical models (Xie et al. 2010).

The major strength of the BIM, the storage of comprehensive information and 3D geometry is used by the research study. With the aim of to improving the BIM data management ability, the new data management of the BIM model will be explored. The virtual prototype system makes use of 1) 3D geometry model for visualization and 2) selection of useful information from BIM data for the dynamics analysis during construction. Details of the proposed BIM use are discussed in Chapter 4.

2.7 Virtual Prototyping

Manufacturing and construction are inextricably linked with each other in the construction industry. How product development is achieved in the manufacturing industry resembles the project development process in construction. In product development, there are five steps: product planning, conceptual design, detailed design, process planning, and commissioning of the product into production (Zorriassatine et al. 2003). As for construction, the five major steps are feasibility study, preliminary design, detailed design, construction and post construction.

As with construction projects, manufacturing faces challenges as well when changing engineering designs into the final project on the factory floor: components might be avoidably hard to assemble, tolerances might be unrealistic, capabilities available in machines may not be used or not used enough and capabilities or constraints in resources may not have been taken into account (CIMdata 2000).

With the purpose of overcoming these limitations, physical prototypes are generally employed. Nonetheless this approach can be cost-ineffective and consumes much time in generating prototypes which are either hard or impossible to modify as soon as they have been assembled. The digital characteristic of Virtural Prototyping (VP) models integrated with efficient and economical computer processing power, allow revision and optimization of the functionality of the designed components fast, economically and efficiently (Zorriassatine et al. 2003).

Virtual prototyping (VP) comprises the construction and testing of a virtual prototype or digital mock-up that is a realistic computer simulation of a physical product's life-cycle and which can be presented, analysed and tested (Dai and Göbel 1994; Wang 2002). The simulation also addresses the broad issues of physical layout, operational concept, functional specifications, and dynamics analysis under various operating environments (Xiang et al. 2004; Drews and Weyrich 1997).

VP technology has been widely applied to the automobile and aerospace fields with great success (Choi 2004). Taking an automobile as an example; it can be fabricated virtually using the VP technique allowing a number of team members to view the 3D image of the finalized product, assess the design, and the production problems before the start of mass production. VP technology is useful in minimizing cost and time, and improving safety and quality. Nevertheless, the development and application of VP tools in the construction industry (i.e. construction process simulation) has a number of limitations. Sarshar et al. (2004) pointed out three main industrial barriers to VP technique development, including cultural and risk issues concerning information sharing, fragmentation of business interests and the lack of piloting on real construction projects. Huang et al. (2007) suggested that the problem with VP technology uptake was the fact that each construction project was unique in terms of its conditions, requirements, and constraints. Chun et al. (2012) used VP technology for modeling and visualizing the construction processes and allow users to simulate these processes to investigate and identify the potential dangers.

A number of researchers have tried to employ the VP idea in forming effective dynamic construction project planning and scheduling tools. Boussabaine et al. (1997) proposed that Virtual Reality (VR) could be used as a means for site layout and planning. Ye et al. (1999) identified the possible advantages of using VR in the planning process through conducting an experiment. Barsoum et al. (1996) believed that the use of VR models can cause project planners to take every single missing detail into consideration, which they do not normally think of, such as site safety and site access.

2.7.1 Virtual Construction Environment

The Virtual Construction Environment (VCE) model is an integrated virtual planning tool created by Waly and Thabet (2002), which lets the project team undertake major construction process rehearsals and examine various execution strategies in a near realistic fashion before the real construction work starts.

2.7.2 Virtual Design and Construction

Providing a way for contractors to design, construct and operate based on the model, Kunz and Fischer (2005) designed the Virtual Design and Construction (VDC) model integrating the product processes. The use of multidisciplinary performance models of design-construction projects, including the product (i.e. facilities), organization of the project team, and work processes to support explicit and implicit business objectives are involved in the VDC. VDC is said to assist the user to combine products, which could be buildings or items of plant. The user can design, construct and operate the product using the VDC, thereby allowing improvement of project strategy, improvement of constructability, a gain of productivity and rapid identification and the solution of time-space conflicts.

2.7.3 Virtual Faciltiy Prototyping

For the purpose of visualizing the building facilities in the construction planning phase, CIC (2005) developed Virtual Facility Prototyping (VFP). The main focus of the technology is to define methods and design appropriate technologies for the creation of cost effective virtual building prototypes for use in industry and education. VFPs can be used to explore efficient development and to foster innovation through improved communication of the design and construction process information between project team members, including the architects, engineers, contractors, owners and suppliers.

2.7.4 Immersive Virtual Environment

Immersive Virtual Environment (IVE) is a means developed by Penn State University of improving the project planning process via the generation and review of construction plans in a virtual environment (Yerrapathruni et al. 2005). The method has been proved helpful to project planning development and understanding of the schedule while constructability can also be reviewed by the IVE. Different construction approaches and strategies can also be tested by this VP technology.

2.7.5 DIVERCITY

DIVERCITY is the acronym for Distributed Virtual Workspace for Enhancing Communication within the Construction Industry. Through a “shared virtual construction workspace”, this research project studied the prospect of collaboration across international boundaries. Sarshar et al. (2004) demonstrated that the application not only simulated the 4D models of the project, but also simulated the lighting design, acoustic design, energy consumption, site planning, safety issues and provided 4D visualization of building sequences. The construction scheduling simulation-related research within DIVERCITY is called Visual Product Chronology, which allows project managers to assign actors or reserve work spaces to specific tasks in a 3D building object model. Scheduling simulation has provided a number of benefits, including improving communication between contractors and subcontractors, and also informing clients of progress.

2.8 Adoption of Virtual Prototyping

The VP technology applied in this study comprises computer software specially written by the Construction Virtual Prototyping Lab of the Hong Kong Polytechnic University (see www.cvptl.com for more information). By customizing two software systems, CATIA V5 and DELMIA V5 of Dassault Systems, and with the addition of construction-specific functions, the virtual prototyping technology offers a digital demonstration of construction processes and activities. It makes use of current technologies, such as 4D CAD, which simply represent construction progress with regards to 3D models of a building project and the construction schedule, by providing the capacity to visualize the three physical dimensions and time as well as all important dimensions of a construction project including safety, logistics, resources and productivity.

By using VP technology in the construction industry the functions of checking design errors efficiently and modifying them effectively can be performed, and then the construction process can be visualized in the virtual environment in order to present clear and easy to operate 3D construction instructions (Huang et al. 2007). Thus, for the application of process optimization and management simplification of the construction process, VP technology can provide a virtual platform for experimenting with alternative scenarios.

2.9 Summary

An overview of the definition of construction planning and scheduling and the factors which lead to success in these activities have been given. The functions of the critical path method, look-ahead schedule and linear scheduling model for traditional construction planning and scheduling methods have been reviewed. Attention has been drawn relevant drawbacks. The methods described are usually used in current construction practice. Due to their limitations, construction reworks often occur, with the result that much construction management innovation has been carried out. In order to consider construction plan resources relevant planning methods have been investigated such as resource allocation, resource levelling, mathematical method, heuristic techniques, simulation modeling, priority rule scheduling and neural network and genetic algorithms.

Over the past decade, much research utilizing 3D CAD to add time to generate 4D for visualization of the construction schedule, analysis of the working space, sequence and safety and improvement in communication in the construction industry has been conducted. However, the above method does not comprehensively consider resource allocation in addition to planning and scheduling. On VP technology, however, contains construction-specific functions and offers a digital demonstration of construction processes and activities. It makes use of current technologies, such as 4D CAD by providing the capacity to visualize the 3D model and time as well as all other important dimensions of a construction project. These include safety, logistics, resources and productivity. Therefore, it is believed that VP technology can greatly support the research to develop the integrated planning approach for optimizing construction planning and scheduling.

CHAPTER 3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter introduces the methodology for the action research forming the subject of this thesis, i.e. the author's research study. The methodology consists of literature review, conducting interviews and making case studies. An overview of the research is presented first. An outline of the research process then follows and an explanation of why an action research approach was adopted.

3.2 Action Research (AR)

The term "action research" was coined by Kurt Lewin and defined as a series of steps that follow the cycle of planning, the action, fact-finding about the result of the action (Lewin 1946).

Hult and Lennung (1980) defined action research as that which simultaneously assists in practical problem-solving, expanding scientific knowledge in the process, as well as enhancing the competencies of the respective actors. It is performed in collaboration with non-researchers in a real working environment. Research data feedback is a cyclical process of action research, feedback data, more action research, more feedback data and so on. Action research aims at a steadily increased understanding of change processes in social systems and is undertaken within a mutually acceptable ethical framework.

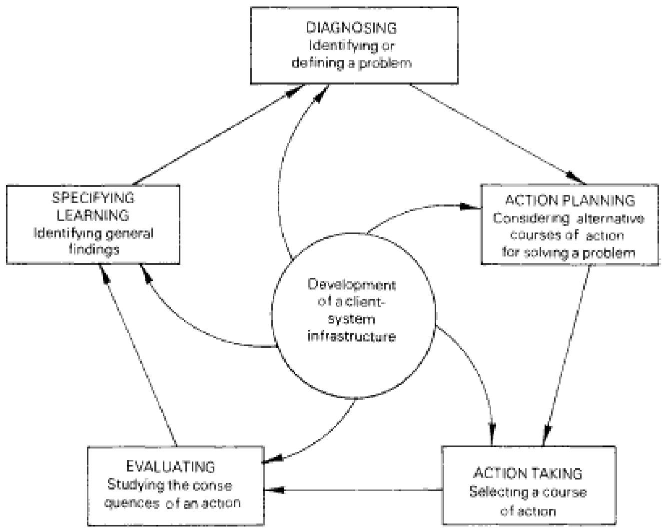


Fig 3.1 The cyclical process of action research (Susman and Evered 1978)

http://www.jstor.org/stable/2392581?seq=7

Most literature reviews on action research describe a five phase cyclical process as shown in Fig 3.1 (Susman and Evered 1978). A detailed description of the cyclical process is given below (Baskerville 1999):

(1) Diagnosing

The diagnostic stage involves the identification of the primary problems or areas of concern which is a self-interpretation of the complex organizational problem. The process is not one of reduction and simplification. Instead, it is performed in a holistic fashion. Some theoretical assumptions (i.e. a working hypothesis) must be developed regarding the nature of the organization and its problem domain.

(2) Action Planning

Researchers and practitioners work hand in hand in the action planning. Through collaborating with one another, this activity points out organizational actions that possess the ability to solve or improve the primary problems identified. The theoretical framework leads the process of identifying the actions to be planned. It gives the desired future state for the organization as well as the changes that would help realize that state. The action plan sets the target for change and the way to change.

(3) Action Taking

In the action taking stage, the researchers and practitioners work together in the client organization. There are different intervention strategies that can be utilized, to effect change, either directive (researcher directs change) or non-directive (change is achieved indirectly). The process draws upon social psychology, such as, engagement, unfreezing, learning and reframing.

(4) Evaluating

Through the collaborative outcomes evaluation by researchers and practitioners, aims to check if the theoretical effects of the action are achieved, and if these effects help with the problems. If the change has been successful, the evaluation must thoroughly assess the action carried out, among the myriad routine and non-routine organizational actions is the only reason of success. If the change is unsuccessful, some structure for the next iteration of the action research cycle (including adjusting the hypotheses) should be set.

(5) Specifying Learning

Though specifying learning is officially the last activity, it is not a one-off process and it usually happens throughout the cycle. Knowledge is obtained during the process of action research (regardless of whether the action is successful or not). The action research cycle can continue, no matter the action is successful or unsuccessful, to develop more in-depth knowledge regarding the organization and checking if the related theoretical frameworks are valid.

3.2.1 Advantages of Using Action Research

Three major benefits of AR are discussed. First and foremost, it offers a detailed explanation of “how” and “why” phenomena (re the problem under investigation) occur. The reasons sometimes cannot be revealed through statistical or regression models. Secondly, research problem(s) are examined in the real natural setting, which although costly is difficult or impossible to replicate in a laboratory setting (Hales and Chakravorty 2006). The third benefit is that action research offers a platform for properly engaged researcher-practitioner collaboration which is a good way for the construction industry to discover solutions which are practical and can be adopted (Azhar at el. 2010).

3.2.2 Disadvantage of Using Action research

Action research (AR) possesses its own shortcomings for the researchers. A problem of AR is that it essentially assumes that an espoused theory commonly determines the actions to be taken. Another shortcoming is that the results from an individual study may not be generalisable (Hales and Chakravorty 2006). On the other hand, real-life cases are still valuable for refining theories and proposing directions for future investigations (Stake 2000). The research therefore is not likely to be a client's first choice which potentially affects the research execution. A conflict may arise when results are not practicable. To know when the research should be discontinued may be hard in cases where the client would like to further the research beyond the original scope. This situation can be avoided by defining the research scope, the roles and responsibilities of the researchers and practitioners, and the endpoint of the research, in a clear and explicit research agreement (Avison et al. 1999; Stringer 1996).

Despite these problems, action research answers the need for relevance in information systems research, and offers beneficial experience for researchers to work hand in hand with the practitioners. In addition, the nature of participatory action research involves researchers as well as practitioners in the research steps, and provides the research community with a more fulfilling experience. In addition, within the real setting of overcoming a pressing issue, action research enables theory to be developed and tested with the input also of practitioners' comments. This clearly proves this competent research method for the PhD study.

3.3 Literature Review

Sekaran (1992) considered the literature review to be preliminary data collection. The literature review was a vital part of this study because it gathered data relating to relevant to the study's parent disciplines and about recent construction planning and scheduling technologies and VP technology that provided the study's theoretical base and helped to uncover related sources for developing a structure. The literature review can be found in Chapter 2. Chapter 6 describes the literature related to bridge construction.

3.4 Focus Group Meeting (FGM)

A focus group, usually contains people with the same characteristics, and is assembled for a guided discussion of some topic or issue (Czaja and Blair 2005). The discussion is moderated by a facilitator, who creates a supportive environment, asking focused questions, to encourage discussion and the expression of differing opinions and points of view (Marshall and Rossman 1999). Morgan (1997) states that "The focus group method is an established rigorous technique for collective interviews aimed at eliciting and exploring in-depth opinions, judgments and evaluations expressed by professionals, experts or user/clients about specific topics." Focus group are likely to include members who either have similar characteristics or experience or are known to have a professional concern about and knowledge of the issues involved (Bell 2005).

In this study, researchers responded to and discovered focus group meeting member attitudes, beliefs and feelings about the VP system model built for construction planning and scheduling. The drawback is that focus group meetings are usually highly unstructured and qualitative data has to be analysed. Content analysis is often used to facilitate the analysis of focus group discussions transcribed text. The method is especially useful for highly unstructured data, and involves grouping communication content into its component parts (Berg 1989).

3.5 Case Study

Case study research usually consists of a comprehensive investigation which often utilizes data gathered over a period of time about the issue in question. The purpose is to analyse the context and process so as to illuminate the theoretical issues being examined (Hartley 2004). For some researchers, the case study suits their needs best as there are opportunities for aspects of a problem to be examined thoroughly (Bell 2005). This method is utilized when the researcher needs solid grounds for his argument by analyzing a person, a group of persons, an organization or a particular project (Naoum 1998). The issue of interest investigated in a real context which often means there are a number of qualitatively different contextual variables that no single survey or data collection method can encompass (Fellow and Liu 2008). Critics argue that case studies possess various problems including the difficulty in cross-checking information, selective reporting and distorted results (Bell 2005).

In this research, a case study was used to demonstrate the use of the VP system for optimizing construction planning and scheduling. The approach provides a practical platform for validation and refining the model.

3.6 Site Validation

The researcher traditionally, collects information from the planner and the research is usually completed in the office. After one to two weeks, the planner assesses the framework. If the product is not up to standard, the researcher changes the framework accordingly. However in the real construction situation, site work details can change, causing the researcher's framework to be inefficient and the framework to fail to meet the planner's needs.

In order to improve the development efficiency of the research and obtain a more usable and practical solution for the planner, site validation is a new research method and process, now being used. This process is part of this research study. It is suggested that the researcher should work with planners and engineers full-time in the construction office during the whole development (two to four months). The details of the steps involved are as follows 1) collaborate with project staff to obtain feedback and current problems, 2) adjust the framework to achieve any current critical issues 3) implement and test the ongoing frameworks.

In this research, the end-user of the VP system is the project planner. Researchers need to fully understand the needs and requirements of construction personnel in the course of the construction project. Though the researcher has rich experience in both theory and practical construction, he cannot guarantee to fully understand the course of individual project.

Each project obviously has unique requirements and constraints. The project planner is key to fully understand fully developments as construction information such as design changes and construction problems may take place every day.

Therefore, the most updated information is immediately within his grasp. Through working with the planner, the researcher can get immediately 1) the latest information, 2) the newest and clearest requirement, 3) testing and validation of tools in place, 4) the latest feedback. As a result he can provide the researcher with a platform to test various construction plans.

3.7 The Thesis Research Process

In this thesis, action research was selected as the research method to provide opportunities for developing an integrated planning solution which captures the characteristics of the planning process. The detail of the research methodology framework is shown in Fig 3.2. The research was conducted in four interrelated steps which are discussed in the following paragraphs.

3.7.1 Diagnosing

The diagnosing stage of action research can be defined as the identification of the primary research problem. The diagnosis was assessed through a literature review to identify the gaps in our knowledge and gaps between what planners really need and what current software systems can provide. A Focus Group Meeting (FGM) was held to identify the planning methods used and find out what is needed to validate the research objective.

The literature review presented in the previous chapter justified the needs for the research and identified those research enquiries needed to develop the research objective of the study of construction planning and scheduling by employing 4D, BIM and VP applications.

FGM was applied as one of the research methods for data collection. Practitioners from Chevalier Construction were members of Focus Group Meeting Team A. Through focus group meetings of Team A (FGM-A), the researcher was able to identify the important players and associates that cover all major sectors in the construction process. The FGM-A members included two project managers, two construction engineers, one project coordinators, one site-agent and one sub-contractor (formwork design). The first session of the FGM-A consisted of comments from previous projects and research which were collected to clarify the strengths and limitations of VP so as to find out the areas of improvement needed. The second session of the FGM-A was a focussed discussion on the question "Which resource analyses should be performed when carrying out construction planning and scheduling?". In order to handle the data, each point should be agreed by all participants. The reason of using an open-ended question was to draw out the critical points for consideration when carrying out construction planning and scheduling. All points obtained should be taken into account without weighing their relative importance Chapter 4 presents the results of the focus group meetings in detail.

3.7.2 Action Planning

In action research, diagnosis leads to action planning. In this research, action planning was used to develop the framework for integrated planning. Based on the data collected from the diagnosing stage, critical issues were added into the framework. In addition, different critical issues were analysed and developed in order to achieve efficient optimization of construction planning and scheduling.

Different models of the approach were developed for the optimization processing. Lastly, the existing application i.e. virtual prototyping was selected for support of the framework. These are discussed in Chapter 4 in detail.

3.7.3 Action Taking

In this research, action taking took the direct intervention form in the application of the integrated planning solution prototype on a real-life case study project to assess its effectiveness. The application of the framework received input from the FGM-A before, during, and after application. Detailed information about the case study and the results are discussed thoroughly in Chapter 5.

3.7.4 Evaluation and Learning

Once an action has been taken, the outcomes are evaluated to determine the knowledge gained in order to plan the next iteration if necessary (Perkinson et al. 2010).

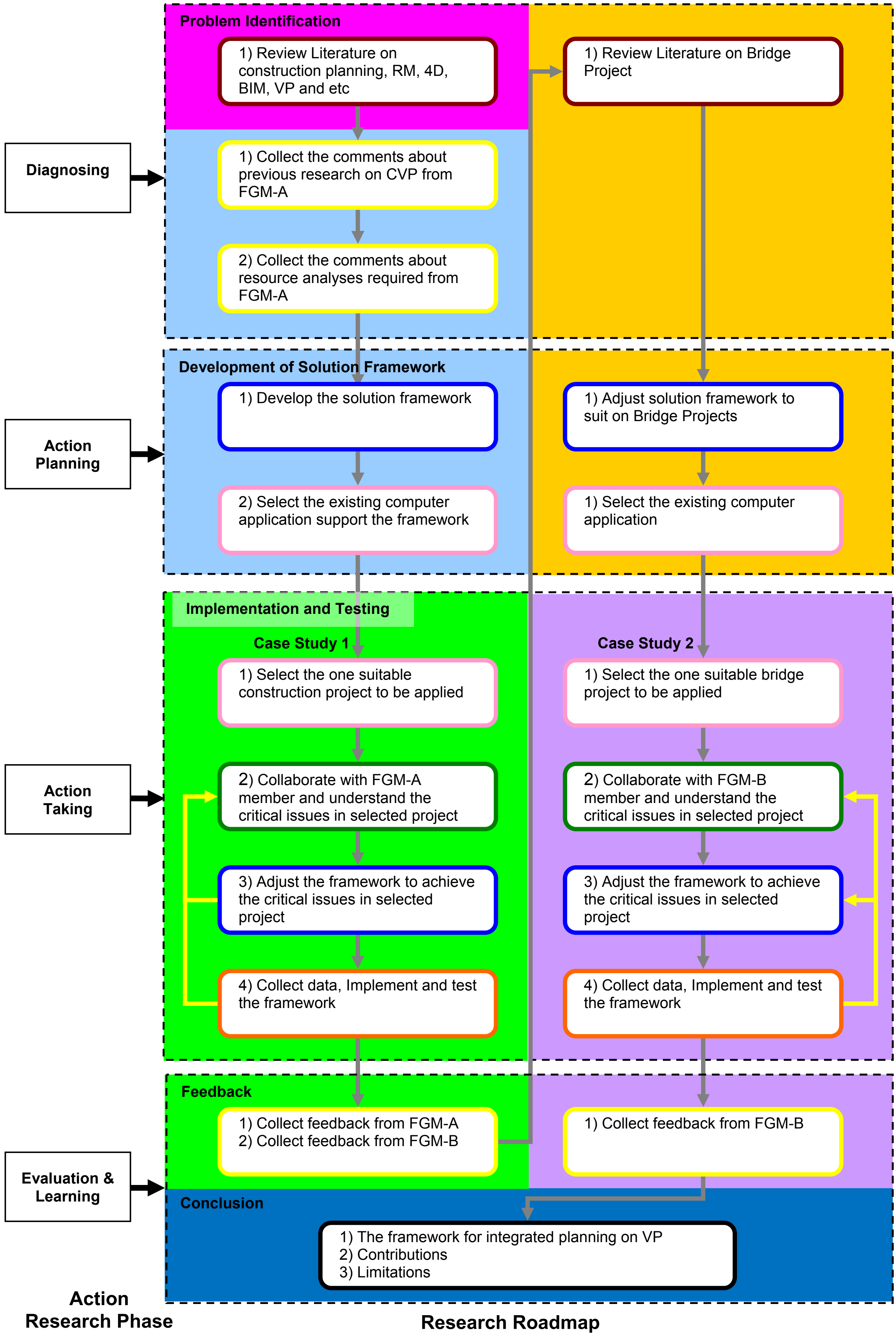
In the author's study, the proposed solution framework was applied on a real-life case study project and the VP results presented to the focus group. The focus group members evaluated the effectives of the system. Their feedback was collected for further improvement and further research which is discussed in detail in Chapter 5.

In order to make the research findings more comprehensive, another Focus Group Meeting (Team B) from Gammon Construction was held to elicit comments and feedback on the case study. The members of FGM-B included two project managers, three construction engineers and one project coordinator. Based on their comments, the next iteration of the action research cycle applied the solution framework to a bridge project. The process of diagnosing, action planning, action taking and evaluation was repeated. The details of the process are given in Chapter 6 (diagnosing and action planning) and Chapter 7 (action taking and evaluation).

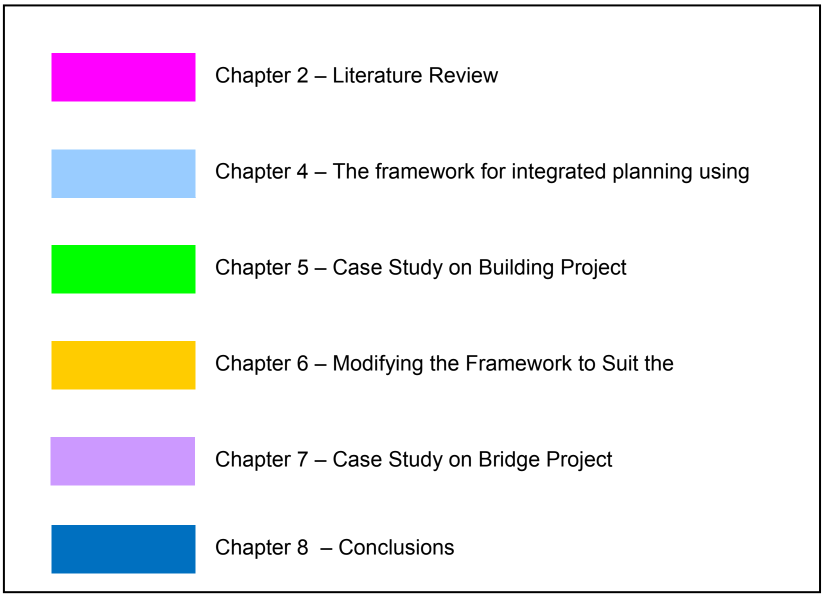
After finishing this process, the learning had been achieved. The project demonstrated ways of optimizing construction planning and scheduling using VP technology. As a result of the process, the focus group members had the opportunity to learn about the new technology and how to apply VP to other similar projects. The thesis contributions relate academic research as discussed in detail in Chapter 8.

3.8 Summary

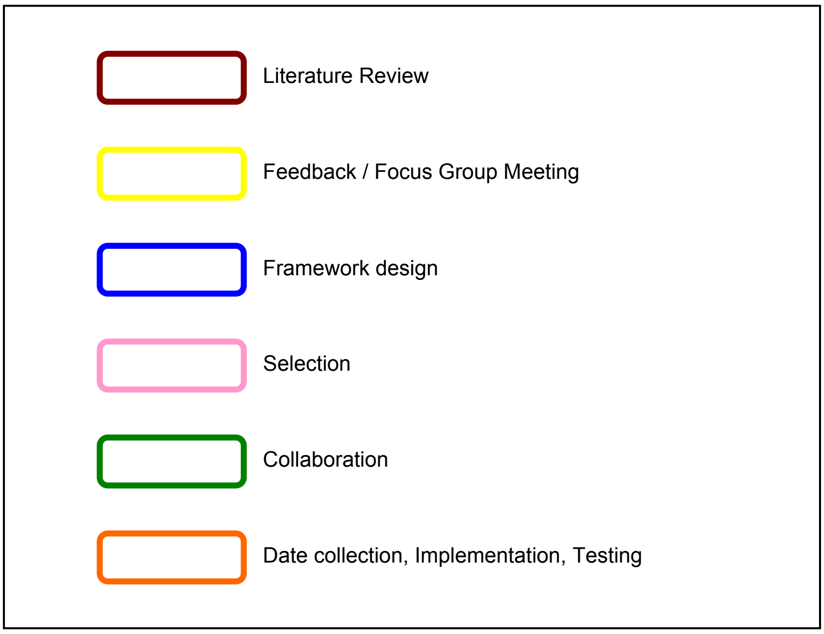
The action research method was used as the overall approach in the conduct of the research study. Other research methods including literature review, focus group meetings, and case studies are grouped under the action research heading. This chapter discusses how the methods are linked with others in the research process. The following chapters introduce how the framework for the integrated VP technology based planning was designed to achieve the aim of optimizing construction planning and scheduling.


Problem Identification
1) Review Literature on construction planning, RM, 4D, BIM, VP and etc
1) Review Literature on Bridge Project
Diagnosing
1) Collect the comments about previous research on CVP from FGM-A
2) Collect the comments about resource analyses required from FGM-A
Development of Solution Framework
Action Planning
1) Develop the solution framework
1) Adjust solution framework to suit on Bridge Projects
2) Select the existing computer application support the framework
1) Select the existing computer application
Implementation and Testing
Action Taking
Case Study 1
1) Select the one suitable construction project to be applied
2) Collaborate with FGM-A member and understand the critical issues in selected project
3) Adjust the framework to achieve the critical issues in selected project
4) Collect data, Implement and test the framework
Case Study 2
1) Select the one suitable bridge project to be applied
2) Collaborate with FGM-B member and understand the critical issues in selected project
3) Adjust the framework to achieve the critical issues in selected project
4) Collect data, Implement and test the framework
Feedback
Evaluation & Learning
1) Collect feedback from FGM-A
2) Collect feedback from FGM-B
1) Collect feedback from FGM-B
Conclusion
1) The framework for integrated planning on VP
2) Contributions
3) Limitations
Action Research Phase
Research Roadmap

Key of the diagram



Key of the box



Key of the Arrow

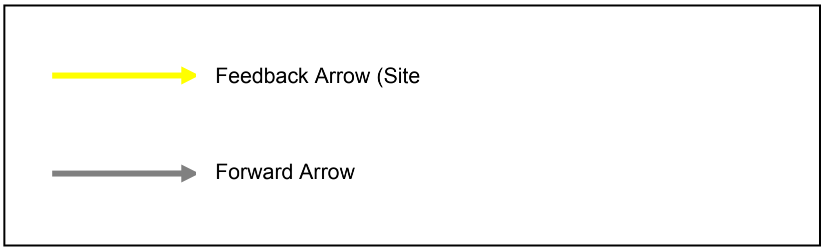


Fig 3.2 The detail of Research methodology framework

CHAPTER 4 THE FRAMEWORK FOR INTEGRATED PLANNING USING VP TECHNOLOGY

4.1 Introduction

In this chapter, the framework for integrated planning using virtual prototyping (VP) technology is discussed and its development presented in detail. First of all, the Focus Group Meetings (FGM) were held to collect two types of data: 1) comments on the advantages of the VP approach of Huang's (2008) research and 2) their comments about resource analysis. Using these data, the structure for integrated planning was designed for optimizing construction planning and scheduling.

4.2 Focus Group Meeting Team A (FGM-A)

Huang's research (2008) developed an integrated framework and a process for applying new virtual prototyping techniques to improve the constructability of the design, the feasibility of construction methods, and the accuracy of construction scheduling, which is iterative inquiry process that consists of planning before the action, applying the action, and reviewing after the action. The new techniques have been developed by The Hong Kong Polytechnic University in the form of a Construction Virtual Prototyping (CVP) System, which is a construction process simulator based on the "Dassault Systemes®" software. This thesis research has brought several benefits to the construction industry. Comments from previous research were collected together to facilitate the development of a solution framework for optimizing construction planning and scheduling. A FGM-A meeting was held to discuss eight CVP application advantages. The participants discussed the eight advantages one by one. The discussion continued until a consensus was reached and a consistent conclusion achieved.

4.2.1 First FGM-A to Discuss the Advantages of Virtual Prototyping

The eight advantages of VP application were discussed by FGM-A (see above). Summaries of the discussion of each advantage are as follows:

4.2.1.1 Design coordination

Design error detection is widely conducted in the construction sector. But in many cases, owing to various constraints (e.g. incomplete information, limited time, inexperienced designers), the effectiveness is relatively low. CVP provides a more effective environment for detecting errors owing to its 3D presentation. It is relatively easy to detect design errors in advance, by simulating construction operations in the 3D virtual environment. Design errors which hinder construction can be efficiently detected and corrected in advance thereby preventing future significant rework.

Feedback from interview: It is a great advantage but at present, all BIM applications also provide similar functions such as design coordination and clash detection.

4.2.1.2 Constructibility review

The 3D models supported engineers in detecting design problems by linking the 3D models to preliminary schedules. The resulting 4D models help project engineers to evaluate the overall constructability of the design by simulating alternative construction sequences.

Feedback from interview: Construability review using 4D simulation is not well-used. 4D CAD shows the construction sequence but this cannot identify the clashes over time. Clashes include plant and activity clashes for example: 1) clashes during transportation; 2) Competition for tower crane service such as hoisting rebar bundles, formwork, concrete skips, etc.

4.2.1.3 Schedule creation

CVP models are helpful in visualizing schedule constraints and opportunities for schedule improvements through the re-sequencing of activities or re-allocation of workspace.

Feedback from interview: Through visualization of the schedule, opportunities for planning optimization can be identified. However, success relies quite heavily on the human skills and knowledge in locating the problem areas.

4.2.1.4 Construction schedule review

CVP models helped the project team analyse the schedule and visualize conflicts that were not apparent in the Gantt charts and CPM diagrams. The planners used the CVP models to simulate the schedule and in this way could easily detect conflicts regarding spatial constraints or resource use. Conflicts were dealt with by changing the activity sequence and then re-evaluating the milestones within the schedule.

Feedback from interview: It is useful in the planning process. But it is far from perfect since some of the activities in construction are not represented in the 3D model. It is also not always easy to identify incidental, but essential work such as casting and welding. However, VP remains a valuable tool for planning because the construction schedule can include such activities if thought desirable.

4.2.1.5 Team communication

Effective communication is of vital importance to the successful undertaking of modern construction projects. Engineers visualize planning ideas by incorporating them in 3D models so that other participants within the planning process can understand the ideas of others more quickly.

Feedback: There is no doubt that the 3D environment can provide visualization functions useful for all participants. Through the platform, they can have a better understanding and reduce communication barriers so as to smooth the workflow.

4.2.1.6 Visualized work instruction

With the assistance of CVP, construction plans can be rehearsed in advanced and an optimized plan chosen before actual physical building begins. CVP models provide a visualized schedule and work instructions to assist site personnel at brainstorming sessions and discussions about access, storage and sequencing of the work.

Feedback from interview: The use of visualization for instruction conveying is better than pure verbal communication as the images facilitate the workers' understanding of the work instruction. If this technology can be applied to safety training, the benefit is assumed to be significant.

4.2.1.7 Detection of unsafe areas

By using CVP, unsafe areas can be more effectively detected in comparison with traditional methods. By virtually walking on the site near working areas, unsafe areas can be detected in advance. The advantage should not be overstated, because given time and sufficient knowledge. It would be possible to detect all potentially unsafe areas from 2D drawings. But CVP makes this easier and more effective.

Feedback from interview: A virtual platform is provided for users to walk-through the site area in the computer to detect areas that are considered unsafe. The pitfall of the system is that it lacks the ability to determine the safety of an environment. The ideal version of the system would spot problem areas automatically. In fact, there are a number of safety requirements and rules and many of them have not been included in the application under study. Many areas of the system should be improved if future application of the software is desired. In conclusion, the mentioned advantage has immense potential which is not fully realized for the time being.

4.2.1.8 Visualization support for clients and public

Clients needed to make accurate and understandable presentations that communicated complex information to a variety of technical and non-technical audiences. In particular when dealing with other agencies, these presentations must communicate the right information in the most effective manner. With the CVP model, the project team was able to create impressive and effective visualizations without the usual long lead-in time and high cost.

Feedback from interview: CVP can provide visualization support, but the result of the VP is quite technical. The public, for instance, who are in fact laypeople would have a hard time understanding what has been done in the simulation process. Nevertheless, it is still far easier to understand than a 2D drawing-presentation. With more simplification and more annotations the presentation would be more suitable for layperson use.

4.2.2 Second Session of FGM-A. Discussion about Resource Analysis Required during Construction Planning and Scheduling

In order to develop the framework enabled resource analysis solution, it is necessary to know what is the nature and degree of the resource analyses needed. In this section, the open-ended question is discussed, "Which resource analyses should be performed when carrying out construction planning and scheduling? The several resource analyses that need to be carried out are summarized as follows:

4.2.2.1 Allocation of Tower Crane

The tower crane is often the most critical component in construction planning and scheduling. In the critical path for high-rise buildings, items that are related to tower cranes are usually of utmost importance. The tower crane hoists materials, concrete, steel bars, formwork and scaffolding especially for the heavy prefabrication units and large panel formwork. Allocation of tower crane time is critical to timely and safe completion of construction.

4.2.2.2 Allocation of access road

Logistics is also a problem facing many construction practitioners. In HK, there is usually limited working area space as well as limited road access roads for material transportation such as ready mixed concrete truckmixers and trucks carrying materials, reinforcement rebar and façade elements. A comprehensive materials transportation plan is therefore needed if construction is to run smoothly.

4.2.2.3 Space Analysis

Activities utilize working space and most materials need space for storage. The space analysis is important to ensure planning feasibility. Also, the time-space may conflict between activities. The working and storage spaces required change dynamically over time on most construction sites. If these changes are not well planned, clashes can easily occur.

4.2.2.4 Productivity Rate

Determination of the resources needed is difficult as all activity duration estimates are based on the experience of the project managers and individual project managers make different judgments. If a project manager is experienced, the estimate would be better. Otherwise, the estimate may differ significantly from the real needs. Both underestimates and overestimates will cause a company to lose not only money and time but also its image. The reason for this type of error is that project managers lack solid ground for activity duration estimating. Therefore, a productivity database support system is an essential element for good planning.

4.3 Using Virtual Prototyping

Virtual prototyping (VP) technology possesses great potential to combine construction planning and scheduling with resource analysis. Currently, VP technology assists project planners to identify construction methods and prepare construction schedules (Huang et al. 2007). To enable simulation of the construction process, the use of DELMIA is proposed. DELMIA is a virtual prototyping application in manufacturing. DELMIA is part of a product lifecycle software tool for managing resource requirements from design to production and maintenance. The core of DELMIA is a product, process and resources model that links up with various application such as 3D model design, process planning, resources planning, discrete and continuous event simulation, 3D visualization, layout planning and virtual reality, all on the same platform. The DELMIA application has been customized to suit construction use by a PolyU team, of which the author was a member. The DELMIA V5 environment is implemented using Visual Basic for Applications (VBA) and Microsoft Excel for the development of construction planning with the 3D Model. VBA is an object-oriented programming language for the development of specific functions. VBA provides a seamless link between the components of the model, supported by a powerful graphical user interface (GUI).

4.4 The Structure for Integrated Planning using VP Technology

4.4.1 Definition of the Construction Model

There are two types of digital model for construction. The first is Building Information Modelling (BIM) which helps evaluate performance by using information embedded in 3D models. The key function of BIM in the construction field is to allow project planners to view static realistic images and check for design errors and collisions. Temporary works are a critical element in construction planning (Koo and Fischer 2000) and this type of model is used to develop temporary work models based on parametric models. Details of a temporary work model are available in Huang et al. (2007).

The second type of digital model is a detailed building components model, which is related directly to construction activities. The purpose of this model is to act as a design check and it is closely associated with construction planning and scheduling. This type of model decomposes serial assembly models to develop detailed construction activity. The decomposition of a product is a precondition for simulation and the chosen assembly of parts must closely relate to the simulation process. For example, assuming the purpose of a simulation is to display the pouring of concrete sequence, for example, one floor of the 3D concrete model will be decomposed into different assembly models (i.e. inner slab, half of outer slabs, outer wall, inner wall, each column) which relate to the actual construction work breakdown and therefore suitable for computer simulation (Fig. 4.1).

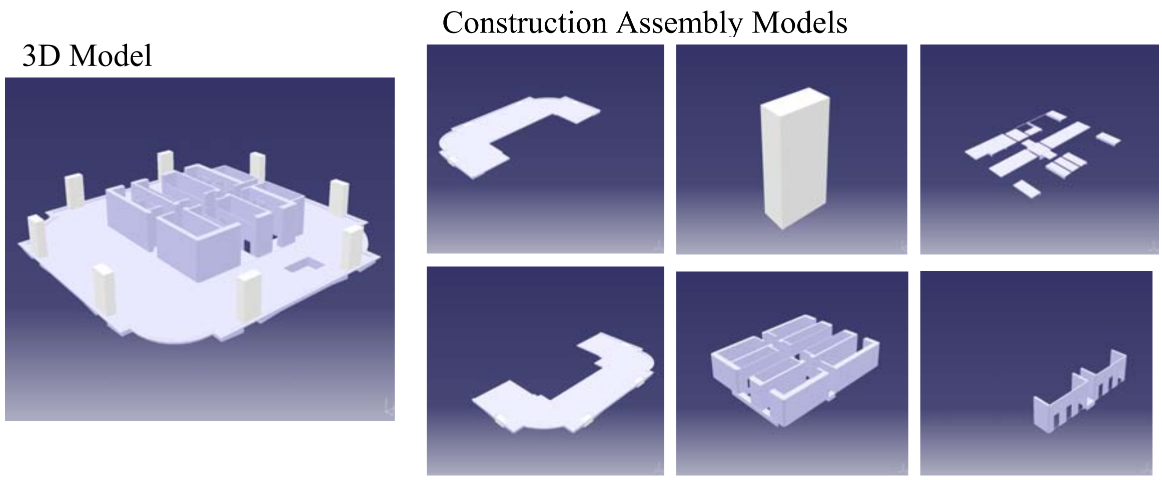


Fig 4.1 Decomposition of 3D building model

4.4.2 Definition of the Resources Model

Two resources models can be identified: an equipment-based model and an activity-based model.

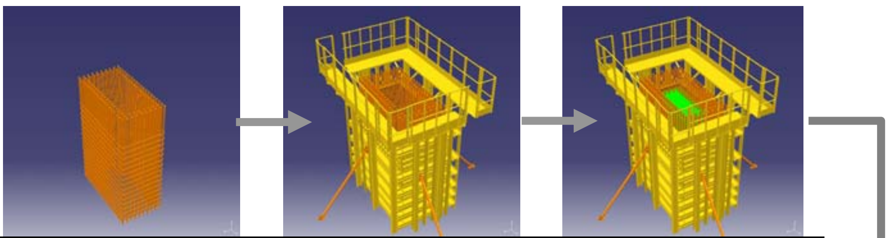
Equipment-based model - The equipment-based model is a 3D geometry model linked to a productivity of equipment Excel library database and physical capacity data. For example, the tower crane model contains graphical information on the geometry, shape and dimensions needed for space capacity analysis (i.e. maximum capacity, maximum lifting height and maximum radius).

Activity-based model - The activity-based model is a non-physical model linked with productivity rats in an Excel library database. The fixing of reinforcement activity is an example. The activity-base model is linked with the construction model by users when generating the VP simulation for that activity.

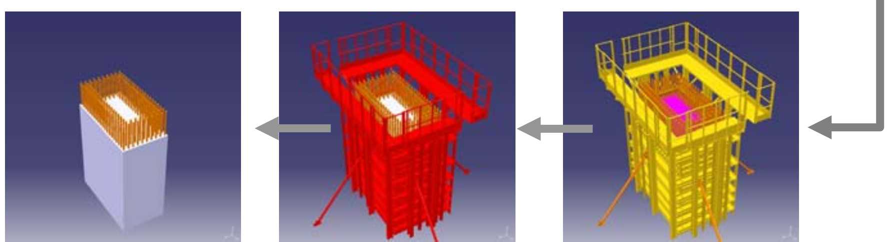
4.5 The Importance of Detailed Simulation

It is important for the simulation of construction that the work involved is broken down into suitably detailed activities. A master program does not include activities in sufficient detail. Activities should be elaborated to the extent that more detail is required for simulation to be realistic. In construction planning and scheduling, it seems very difficult for project planners to deal thoroughly with detailed activity, resource allocation and space requirement considerations. Project planners pay a lot attention to the master program but tend to neglect detailed activities. They understand that resource allocation is a key factor in construction planning and scheduling but lack mathematical methods with which to determine an optimum resource allocation. The space required by construction activities is the most difficult since the spaces available change as a project proceeds in intermittent fashion. Since spaces required by activities change intermittently in all three dimensions over time (Akinci et al. 2000; Akinci et al. 2002; Thabet and Beliveau 1994; Zouein and Tommelein 1994), the time-space issues may can result in conflicts between activities.

A detailed 4D planning schedule is required to compute the duration of each activity and the associated space required. The activity "concreting wall" provides a good example (Fig. 4.2). It includes many types of activity related to time-space. Fixing reinforcement rebar, erecting falsework and formwork, pouring concrete, casting concrete and finally dismantling the formwork and falsework which all require processing time, space for crews to work in, short term storage space for the handling of the various material items and working space for the equipment items needed. There are many factors to be considered in this simple activity. All of them are directly related to construction planning and scheduling.



Activity	Fixing rebar	Erecting formwork and falsework	Pouring concrete
Productivity Rate Need	Workers' productivity rate	Workers' productivity rate	Pouring speed and volume



Completed	Dismantling formwork and falsework	Casting concrete
	Workers' productivity rate	Casting time

Fig 4.2 The detailed sequence of concreting wall

4.6 Site-Layout Planning

Site-layout is one of the critical planning considerations. The size of site and locations of temporary areas, access roads, storage areas and working area etc. all directly affect construction planning. The outcome of the optimizing processes using the construction model and the resource model can be transferred to the 3D site-layout. After the setting out of the site boundary VP can analyse the access road, space requirement and working area.

4.7 Implementation

The database of productivity rates for planning and scheduling is stored in Microsoft Excel format. The virtual prototyping system is implemented using Visual Basic for Applications (VBA) in the DELMIA V5 environment, and Microsoft Excel to develop the productivity database and planning schedule linking with the 3D Model. VBA is an object-oriented programming language enabling the development of specific functions. VBA provides a seamless link between the components of the model, supported by the powerful graphical user interface (GUI). The equipment-based model and the activity-based model link with the productivity rates for equipment and for the crews carrying out activities.

4.8 Integrated Construction Planning Schedule, Site-layout Planning and all Construction Process Activities

The 3D site-layout VP model has been developed based on the 2D site-layout plan. Through VP technology, an activity process is generated by linking a construction model and an activity model or by linking a construction model and an equipment-base model. Combining each process activity with the construction plan sequence, along with the 3D site-layout plan, a simulation process is developed (Fig. 4.3).

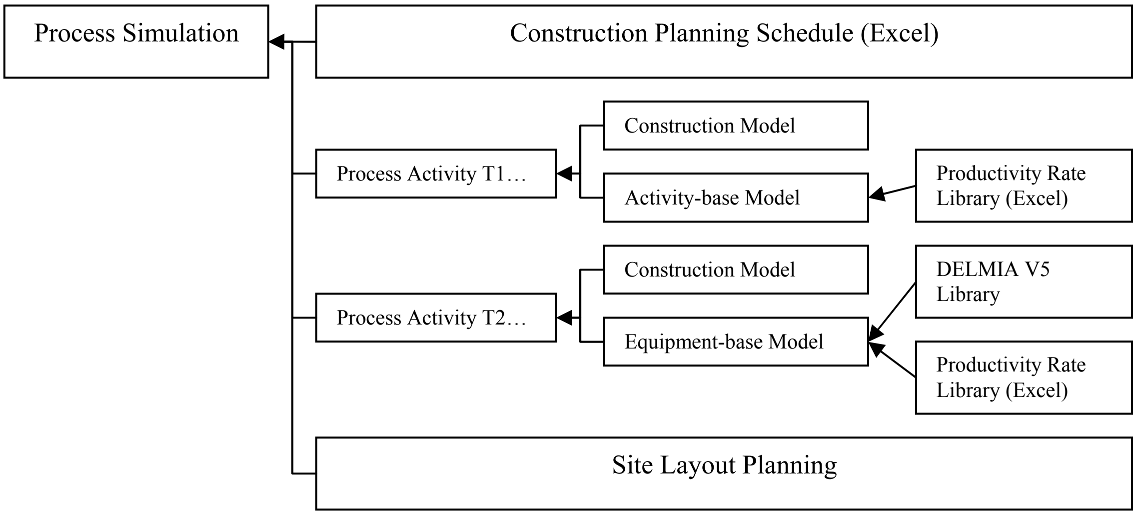


Fig 4.3 Structure of virtual prototyping

4.9 Resource Analysis

In the construction field, all activity duration estimates are based on the experience of the project managers. The duration of activities is therefore often uncertain. One major function of the VP system utilizes real productivity data from the system database to verify and then adjust the resource allocation. Through the process simulation, the requirement for resources, such as space, plant and crews, can be analysed. As stated above the tower crane is the most critical component on many projects. Through 3D visualization and simulation of the tower crane operations, the planner understands the plan in detail and is able to identify any likely problems in advance (Tantisevi and Akinci 2008). The following chapter consists of a case study demonstrating how resource allocation can be achieved.

4.10 Summary

The FGM-A had been held to discuss the results of the previous case studies and the critical factors in construction planning and scheduling. The structure for integrated planning using VP technology was developed from the feedback and comments. In the structure, the BIM model is divided into a construction model and a resource model. The former is a 3D geometry model which can be broken down into appropriate work package components for detailed simulation. The resources model consists of a plant-based model and an activity-based model. These models utilize the characteristics of BIM model for storing useful information for planning analysis use. The whole VP simulation process includes site layout planning, the construction planning schedule activity processes and resource analysis. The next chapter describes how a construction model and a resource model can be prepared for VP in support of the construction planning process. A case study is presented to demonstrate how the construction planning and scheduling is optimized. The purpose of using VP technology for construction simulation is to assist project planners to better understand the construction process and predict potential mistakes.

CHAPTER 5 CASE STUDY ON BUILIDNG PROJECT

5.1 Introduction

In this chapter, a real-life case study is presented which demonstrates the use of VP enabled resource analysis to reallocate space, for access road logistics and the arrangement of tower cranes to achieve a 6-day floor construction cycle. Focus group (Team A) and focus group (Team B) meetings were held and their feedback on the case study results were collected.

5.2 Case Study

The case study involves two residential building projects in Hong Kong. At the time of the research, the foundations of the two buildings were already completed. The site-layout planning had also taken place. During construction, the project managers encountered different types of critical problems while planning the typical construction cycle. They would like to have visualization, digital and mathematical analysis to assess the constructability of the construction planning and scheduling. They provided the researchers with a preliminary construction plan and schedule, for the construction of a typical floor, on a 6-day cycle (Fig. 5.1).

SHATIN PASS ESTATE 6 Day Cycle

Date: 28-11-2007

	1		2		3		4		5		6	
1A	7:00 - 8:00 7:00 - 14:00 8:00 - 10:30 10:30 - 18:00	L-W-R F-W-R L-I-F I-W-F	7:00 - 15:00	IC-W-F	8:00 - 14:00	P-W-C	7:00 - 18:00 13:00 - 18:00 15:00 - 18:00	D-W-F E-S-F L-W-P	7:00 - 12:00 8:00 - 12:00 14:00 - 18:00	L-W-P E-S-F L-S-R	8:00 - 15:00 15:00 - 18:00	F-S-R P-S-C
1B	7:00 - 12:00	IC-W-F	10:30 - 14:00	P-W-C	7:00 - 18:00 13:00 - 18:00 15:00 - 18:00	D-W-F E-S-F L-W-P	7:00 - 12:00 8:00 - 12:00 14:00 - 18:00	L-W-P E-S-F L-S-R	8:00 - 15:00 16:00 - 18:00	F-S-R P-S-C	7:00 - 8:00 7:00 - 14:00 8:00 - 10:30 10:30 - 18:00	L-W-R F-W-R L-I-F I-W-F

	1		2		3		4		5		6	
2A	7:00 - 18:00 13:00 - 18:00 15:00 - 18:00	D-W-F E-S-F L-W-P	7:00 - 12:00 8:00 - 14:00 14:00 - 18:00	L-W-P E-S-F L-S-R	8:00 - 15:00 15:00 - 18:00	F-S-R P-S-C	7:00 - 8:00 7:00 - 14:00 8:00 - 10:30 10:30 - 18:00	L-W-R F-W-R L-I-F I-W-F	7:00 - 15:00	IC-W-F	8:00 - 14:00	P-W-C
2B	7:00 - 12:00 8:00 - 14:00 14:00 - 18:00	L-W-P E-S-F L-S-R	8:00 - 15:00 15:00 - 18:00	F-S-R P-S-C	7:00 - 8:00 7:00 - 14:00 8:00 - 10:30 10:30 - 18:00	L-W-R F-W-R L-I-F I-W-F	7:00 - 15:00	IC-W-F	11:00 - 15:00	P-W-C	7:00 - 18:00 13:00 - 18:00 15:00 - 18:00	D-W-F E-S-F L-W-P

Remark:

L-W-R Lifting wall rebar
F-W-R Fixing wall rebar
L-I-F Lifting and installing façade
I-W-F Installing wall formwork
IC-W-F Installing and checking wall formwork
P-W-C Pouring wall concrete
D-W-F Dismantling wall formwork
E-S-F Erecting slab formwork
L-W-P Lifting working platform
L-S-R Lifting slab rebar
F-S-R Fixing slab rebar
P-S-C Pouring slab concrete

Fig 5.1 Time slot – construction planning

The building would have prefabricated concrete facades supported by in-situ concrete walls, a lift core and half an in-situ slab. The two buildings were named No.1 and No.2 respectively. The project managers divided the buildings into two working bays in the middle. The bays of building No.1 were named 1A and 1B. The bays of building No.2 were named 2A and 2B. The construction cycles of each bay were adjacent to fully utilize the tower cranes.

A set of steel formwork panels was used for all concrete walls and slabs. The project managers planned to construct the two buildings at the same time but only one set of steel formwork was used. Two tower cranes were installed on the construction site for lifting the formwork panels, prefabricated concrete façade units, reinforcement bars and concrete skips. One tower crane (T1) was installed between Bay 1A and Bay 1B while the other (T2) was installed in the middle of Bay 2A and Bay 2B (Fig. 5.2). The two tower cranes were of different capacities. The maximum radius of T1 was enough to reach Bay 2B whereas the maximum radius of T2 could only reach the temporary storage space. There were two ways of lifting the steel formwork. One was a direct lift from bay 1A to bay 2A using T1. The second was to lift the formwork from Bay 1A to the temporary storage space between the two buildings by T1 and to use T2 to lift the formwork to Bay 2B. For pouring concrete, both Bay 1A and Bay 1B used a tower crane while a concrete pump and placing boom was used in Bay 2A and Bay 2B.

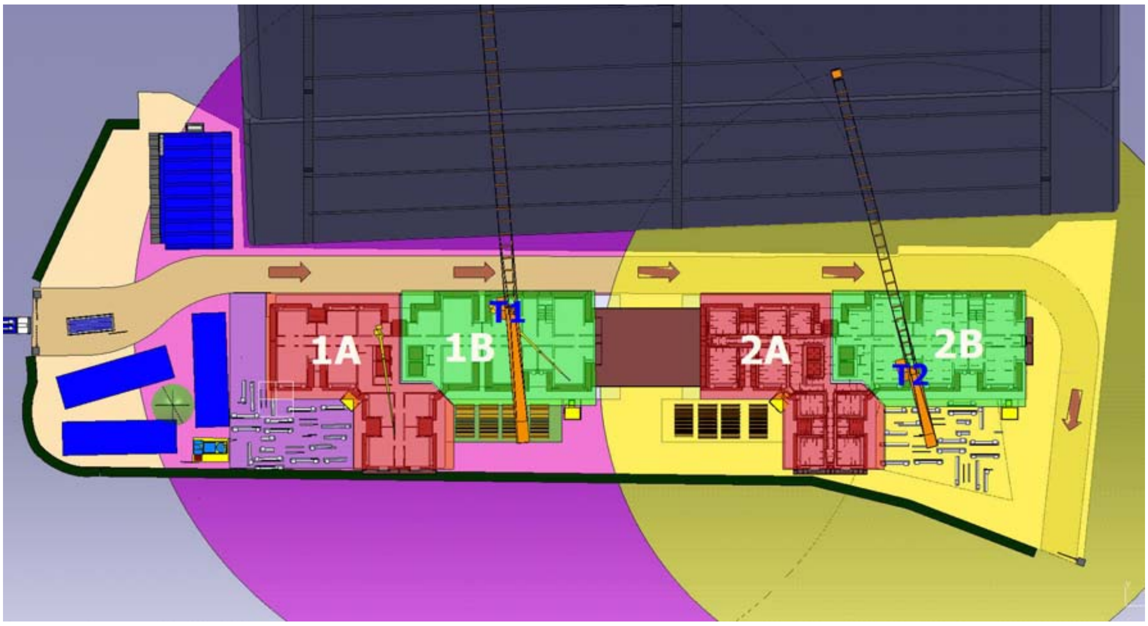


Fig 5.2 The location of the two tower crane and the four bays

The project planners encountered the following critical problems in the planning schedule:

1. There was a limited storage area for facade elements, steel formwork, reinforcement and temporary support; hence it was necessary to plan what materials would arrive, and when and where they would be stored.
2. There was a limited working area for workers and a limited access road for such as transit mixers, and the transportation of reinforcement and façade elements.
3. The initially planned activity durations were not computed mathematically. The project planners wanted to use real productivity rate data to verify the construction planning and scheduling especially for the cranes as they were the critical elements of the whole plan.

5.3 Preparation of the Construction Model and Resources Model

A construction model for temporary work was developed based on the design drawings prepared by the nominated subcontractor and the building components model was based on the process activities when decomposing the final product into suitable sub-assembly models. The two tower cranes and the placing boom were built into the equipment-based model. Their capacities derived from capacity catalogues. The activity-based model was derived easily from the Excel library database since the productivity rates for the activities were available from previous several similar projects.

5.4 Start from Preliminary Construction Planning and Scheduling

The main construction method was the use of one set of steel formwork for the two buildings as explained above, to reduce the cost of steel formwork. However, there was not enough space for storing the formwork. The project schedule was represented by a simple bar chart document. The researchers generated a template of the construction plan and schedule in VP-Excel format for inputting the bar chart schedule data (Fig. 5.3). The planning schedule was imported into the VP system. This allowed the users to link the process activities with their own related construction and resource models (Fig. 5.4)

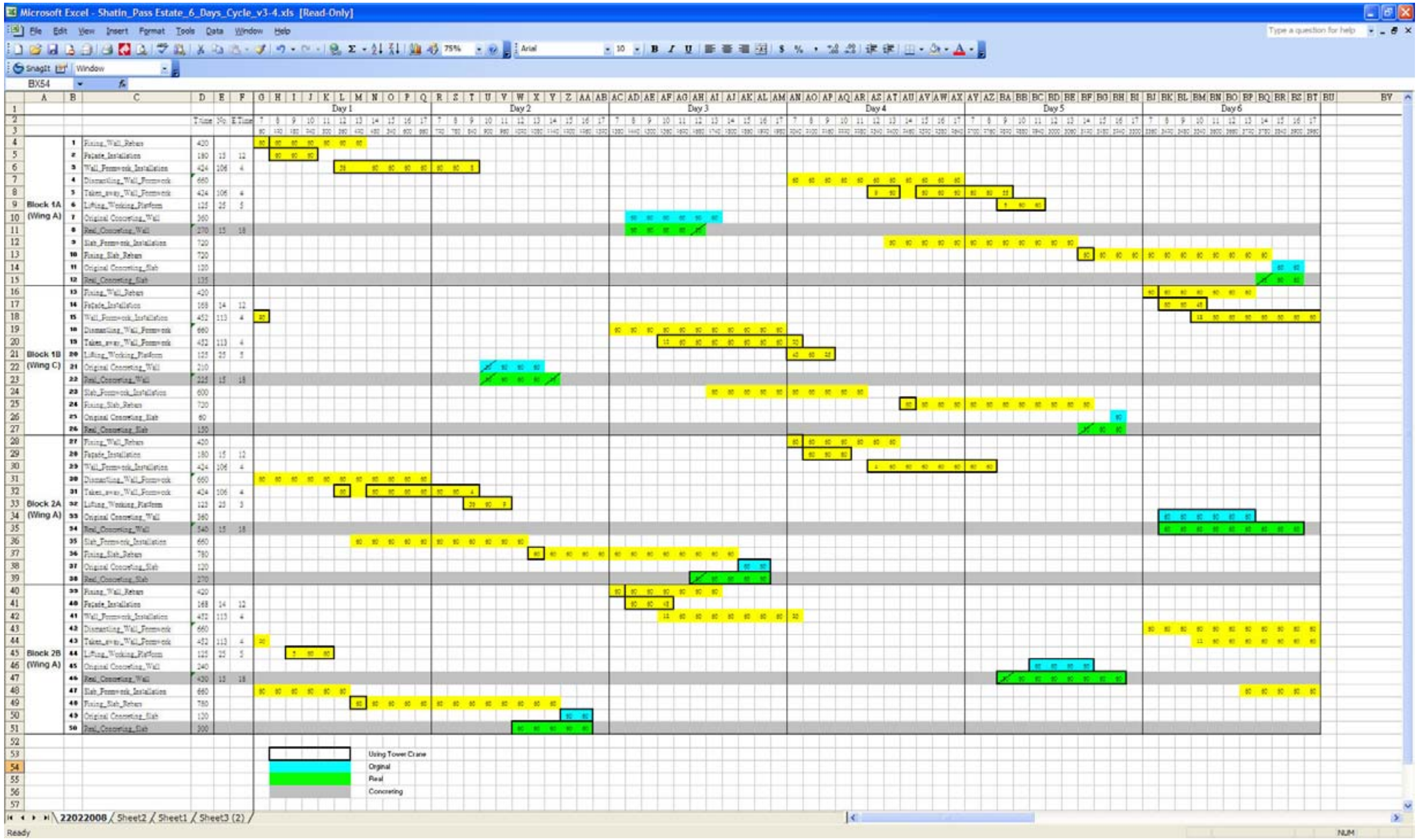


Fig. 5.3. Construction planning schedule for VP-Excel Format

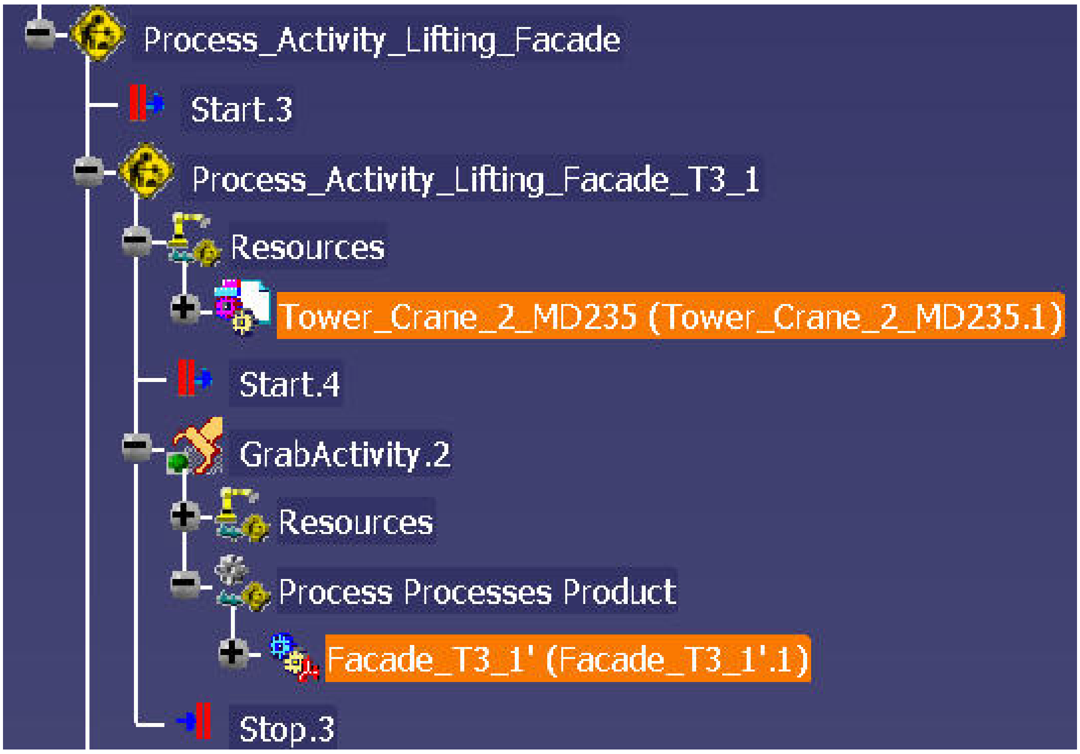


Fig 5.4 Assignment of the tower crane to lift the façade in one process activity

5.5 Build Site-layout Environment

The project planners had finished the site-layout planning before the researchers joined. The 2D site-layout planning was used to build the 3D site-layout environment, including the location of the two different types of tower crane, site office, storage area, passenger and material hoists and access road. The 3D site layout provided a virtual construction site enabling the VP system to analyse the access road, space requirement and the assignment of tower cranes.

5.6 Analysis of the Resource Allocation

By integrating the preliminary construction planning and scheduling, site-layout planning, construction models and resource models, simulation of the construction process was developed to analyse resource allocation. All activity productivity data were obtained from various previous projects. The data was thus objective. Most major activities related to the tower cranes, access road and space. These three factors were applied to these activities. The data included the duration of material delivery, as materials must be delivered to site before planned installation dates to prevent delays to other work. Different types of productivity rate related to these three factors (Table 5-1). The users then defined those activities linked with tower cranes, access road and other spaces in order to check the feasibility of the construction plan and schedule. The results can be generated immediately although the data often vary during the construction process as the framework of preliminary construction planning schedule was imported and the VP system was based on parametric model.

	Tower Crane	Access Road	Space
The capacity of transit mixers	Yes	Yes	Yes
The speed of pouring by using tower crane	Yes	Yes	Yes
The speed of pouring by using placing boom		Yes	Yes
The time of fixing rebar per area			Yes
The lifting time of rebar	Yes		
The lifting time of steel formwork from the building to temporary storage platform	Yes		Yes
The lifting time of steel formwork from 1B to 2B	Yes		
The rising time of the working platform	Yes		
The lifting time of rising and installation of facades	Yes		
Size of steel formwork			Yes
Size of facade			Yes
Area of temporary storage			Yes
Area of storing reinforcement			Yes
Area of storing façade			Yes
Required quantity of reinforcement for 6-day cycle			Yes
Required quantity of facade for 6-day cycle			Yes

Table 5-1 Different type of productivity rates related to three factors

5.6.1 Allocation of Access Road

It was important that there was no overlapping of transportation routes in planning the use of the access road as there was only one access road on the site. The trucks carrying reinforcement/facade and the truckmixers would remain on the access road. In particular, the successive truckmixers would occupy a position on the access road for approximately 10 hours when serving a concrete pour and so would obstruct the road. All types of truck needed to be arranged correctly to avoid any overlapping of transportation routes. In a concreting case, the project planner might choose a placing boom and concrete pump to replace the tower crane to reduce by half the truckmixer parking time as concrete placing speed can be doubled in this way. Pumping concrete also frees up the tower crane for other uses. The VP system computed the number of truckmixers needed based on the required quantity of concrete for the different bays to be concreted and then compared placing by pumping with tower crane and skip placing in choosing how best to achieve the 6-day cycle for each floor. The system focused on all activities to calculate exact durations in simulating the effects of planned access road allocations to identify any conflicts of access road use. Exact and error-free arrival timetables for all types of trucks were then generated which helps keep activities on schedule.

5.6.2 Allocation of Tower Crane

Planning usage of the tower cranes was crucial to timely and safe achievement of the 6-day floor planning schedule as the cranes are involved in lifting items for many and various activities across the site as explained above. Firstly, based on real productivity data, the VP system checked the planned durations of the construction schedule for activities needing the tower cranes and then modified them as necessary. Secondly, based on the preliminary plan the VP system showed where tower crane unitizing activates clashed using the display screen and the Gantt Chart respectively (Fig. 5.5). For example, the VP system detected a clash between installing wall formwork in Bay 1A and pouring wall concrete in Bay 1B both tasks using the same tower crane T1. The site management then adjusted the plan and the schedule to eliminate the clashes.

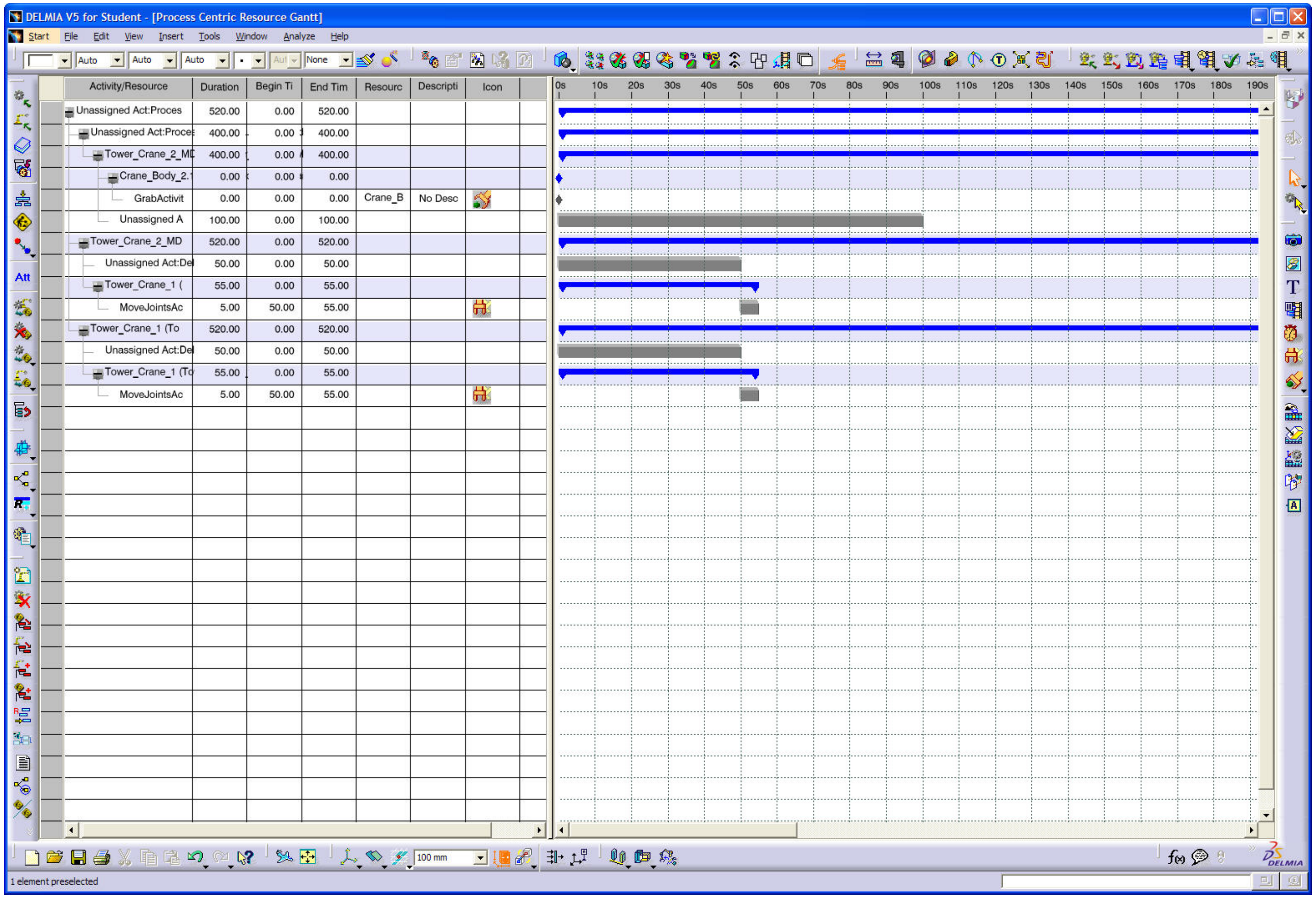


Fig. 5.5 Assignment of two tower cranes in Gantt Chart

5.6.3 Space

The space involved storage of materials, equipment, and working space in 3D through time. Because of the limited construction site area, the maximum quantities of reinforcement and façade units which could be stored needed consideration. The VP system determined the number of truckloads needed based on the required quantity of reinforcement and facade numbers for the 6-day cycle and then computed the storage area needed. Based on availability of the access road, these data were then used to determine the truck delivery schedule.

The project planners had an innovative idea for creating extra space. This was to build a temporary platform for steel and formwork storage for a short period. Through VP technology, the space with time usage could be analysed accurately.

Through the VP system, the project planner obtained a practical and precise plan and schedule. There was also increased confidence that the newly planned allocation of resources would achieve the 6-day floor cycle. The risk of project delay can be minimized with the help of VP based resources analysis.

5.7 Site Validation

Site validation is adopted during the case study to validate the VP system. The researcher works in the construction office full-time with planners for approximately two months. During this time exchange of information is obtained as soon as it is available. The steps of site validation are as follows:

1) collaboration with the planner and to obtain the latest information such as site layout and productivity data;

2) understanding of critical issues such as access allocation, tower crane and space allocation;

3) design of the VP system to meet the given requirements;

4) Implementation and testing of the VP system;

5) receipt of the planner's comments;

6) modification of the framework of the VP system to obtain comments;

7) Looping steps 4, 5 and 6 until the VP system can fulfill the planner's requirements and needs.

5.8 Feedback

Feedback from a member of FGM-B indicates that it would be better if construction planning and scheduling and site-layout planning were integrated within the VP system, so that all three components are derived simultaneously. A good site layout plan can increase the productivity of construction improve safety and avoid obstructing material and equipment movements on the construction site (Sadeghpour et al. 2006; Hegazy and Elbeltage 1999; Tommelein et al. 1992). Comprehensive planning and an efficient site layout are the two initial requirements leading to successful construction management (Chau et al. 2004). A computer-aided environment can support the site-layout planning design. Ma et al. (2005) developed an integrated site planning tool called the 4D Integrated Site Planning System (4D-ISPS) which integrates schedules, 3D models, resources and site spaces together with 4D CAD technology to provide 4D graphical visualization capability for construction site planning.

Feedback from another FGM-B member noted that collision detection between plant was not catered for and this consideration is important when planning. As there will soon be many sizeable and significant infrastructure projects in Hong Kong, the system should be capable of application on civil engineering sites. The value of the system would then be increased. Infrastructure projects are different from building projects, however, and the critical issues are not the same. The differences need to be clearly identified before the VP system can be developed to include infrastructure projects. If this is done, then the less developed parts of the current system should be improved with both buildings and infrastructure in mind.

5.9 Summary

A demonstration of a VP system application showed how a user was able to test, improve and validate a proposed construction plan and schedule. The VP system was used to analyse resource needs and allocate them to prevent interference between the various activities in the cases of access road usage, materials storage and tower crane service. This ability is likely to help prevent a lengthening of the construction period.

Building up full details of a BIM model, however, is a time consuming task for several people. Choosing particular problem models to be built as detailed models is the key to resources saving. Building up the construction model and a resource model database is a very important foundation for subsequent model building as since they may be reused on future projects. According to the feedback received, the VP system is already a good construction planning tool. But there is still a need to develop a good scheduling capability. For example a site-layout planning feature is needed to help avoid clashes in the use of space by plant items, delivery vehicles and labour crews. In the next chapter, an improved and modified framework for integrated planning is described, suited to the needs of bridge projects.

CHAPTER 6 MODIFYING THE FRAMEWORK TO SUIT THE NEEDS OF BRIDGE PROJECTS

6.1 Introduction

This chapter first includes a literature review comparing building projects and infrastructure projects of which a bridge project is an example. The characteristics of bridge projects are defined. The integrated planning framework was modified to suit bridge projects based on the building project case study feedback and the literature reviews.

6.2 Comparison between Building and Bridge Projects

Compared with building projects, bridge and highway construction involve fewer activities and crews. However, the degree of complexity in constructing a bridge or highway is similar to that of a building project. Also, the construction of bridge and highway projects of any magnitude has become increasingly difficult due to the highly competitive environment and complexity of the management process (Shah et al. 2008). Bridge construction involves complex geometric configurations that render communication of project information among interested parties very difficult and prone to errors (Liapi 2003). Applying innovative VP techniques to the planning and scheduling of bridge construction would assist project planner to make better planning decisions.

For bridge and highway construction, Liapi (2003) applied 4D CAD on an actual project to provide a better understanding of the aspects and spatial constraints of the project as this compared with using a traditional 2D format. Similarly, Zhou and Wang (2009) used 4D simulation for bridge construction to provide the user with a construction schedule to forecast resource consumption over time. Park et al. (2009) applied 3D CAD to test construction plans and scenarios to improve bridge constructability, while Kim et al. (2011) have developed 4D CAD at three different levels of detail: the activity, the discrete operation, and continuous operation, for analysing and modelling bridge construction.

Approaches already exist that attempt to optimize construction planning. For example, El-Rayes (2001) and Hassanein and Moselhi (2004) developed an object-oriented model for planning and scheduling highway construction; El-Rayes and Kandil (2005) created a multi-objective genetic algorithm using a three-dimensional time-cost-quality trade-off analysis to identify optimal resource utilization plans and Said et al. (2009) have applied computer simulation to optimization of the planning of bridge construction and the resources involved. Kamat and Martinaz (2003) used a visualization system (VITASCOPE) to produce a 3D animation of equipment operations depicting a set of geometric transformations of pieces of equipment generated by discrete-event simulation.

The emerging technologies may look similar. However, there are significant differences between 4D CAD and computer simulation in the scope for detailed project control. 4D CAD is initiated at the output product modelling level whilst computer simulation focuses on operational level modelling (Kamat and Martinaz 2003). Even when 4D CAD is applied (Liapi 2003), no existing model can optimize construction planning by taking into account the potential for collisions between construction plant and equipment and space conflicts among activities. VITASOPE (Kamat and Martinaz 2007) and virtual prototyping, on the other hand, are effective tools for such conflict analysis at the operational level, enabling simulation of the building component construction and assembly process, Project level and operational level are inextricably linked in practice so the right approach to the modelling of construction planning must cater simultaneously to the both levels.

6.3 The Characteristics of Bridge Projects

Bridge construction involves multiple recurring activities, in the building of foundations, piers and decks (El-Rayes 2001) - processes which are comparatively straightforward in comparison with building projects. While bridge construction involves fewer types of working activities than building construction, it does not necessarily follow that bridge construction is easy. Problems and uncertainties are always likely to occur. Some factors are especially critical, including 1) the relationship between terrain and the proposed bridge, 2) various designs of temporary work such as temporary platforms, 3) determining the number of resources, 4) the cost of the project and 5) duration of the project.

A bridge project is a continuous linear project (Hassanein and Moselhi 2004; Platt 2007), characterized by a geometrically linear layout. . Highway and bridge projects involve an intensive period of earthwork and the topography often changes with the cutting and filling work involved. While building construction projects contain discrete time-linked objects such as columns and slabs (Platt 2007), bridge project activities cannot be clearly identifying and linking with discrete schedule activities is not possible.

In contrast with building projects, many bridges and highways are constructed on a sloped working area (earthwork) such as mountains or hills. As building projects are often carried out on plane surfaces, excavation is made to level surfaces. In bridge projects, excavation is minimized, as it is both costly and environmentally unfriendly, which leads to the challenge of designing economical and efficient working platforms to achieve the maximum productivity of overall construction plans.

6.4 Project-level and Operation Level Details

Kamat and Martinaz (2003) recognized the project and operational levels of detail. At the project level, construction progress is visualized as a set of building components being constructed and assembled over a period of time. At the operational level, the dynamic motion of resources (e.g. crews, pieces of equipment and materials) actually doing the work is visualized.

At the project-level, the common schedule visualization tool is the 4D model, which is a 3D model combined with a time/schedule, to enable planners to visualize the construction sequence and timings. The related research is presented in detail in section 2.4.1 in detail. There is little doubt that the main and direct benefit of 4D model is that visualisation can help to improve understanding of the construction schedule and the communication between clients or colleagues. It cannot, however, provide the analysis or optimisation of plans.

Another important use of 4D is the analysis of spatial conflicts. The completed research in this respect, is prsented in detail in section 2.4.2.2 paragraph 3. Space is one of the elements of 4D, which enables analysis activity conflicts. However, it should be understood that the above research focused only on either the project level or the operations level.

At the operational level, Discrete Event Simulation (DES) systems have been used to improve productivity by minimizing mistakes. Examples include: CYCLONE (Halpin 1977), UMCYCLONE (Ioannou 1989), CIPROS (Tommelein et al. 1994), and DISCO (Huang and Halpin 1995). Kamat and Martinez (2003) also uses discrete-event simulation to develop an approach (VITASCOPE) for generating 3D animation of equipment operations based on a sequence of geometric transformations.

Finally, a considerable amount of research has been aimed specifically at crane operations modelling to identify related spatial conflicts. Sivakumar et al. (2003), for example, present a computer aided path planner for two cranes during material-lifting operations based on a robot path planning algorithm. Tantisevi and Akinci (2007), on the other hand, present an approach for generating workspaces and identifying spatial conflicts for moving mobile cranes. Kang et al. (2009) have also developed physics-based simulation and animation of crane motion showing the erection of steel and precast reinforced concrete buildings to minimize construction time and collisions. In addition, Kamat and Martinez (2001) developed a general-purpose 3D visualization system that enables spatially and chronologically accurate 3D visualization of modelled construction operations and the resulting products. Moreover, Kamat and Martinez (2007) developed a system to identify and report such collisions at the operational level related to construction resources, including plant, in 3D animations of construction operations, while Al-Hussein *et al.* (2006) proposed the integration of 3D visualisation and simulation for tower crane operations. The construction master programme, however, has not been considered. To have an accurate rehearsal of construction operations, the simulation should reflect project level processes in the same way as 4D. Tantisevi and Akinci (2009) presented an approach to generate crane operations based on project-level process information for identifying possible spatial conflicts. However, the research did not utilise the operation of the mobile crane to estimate the lifting time, and failed to use the capabilities of the 4D model to create a detailed construction schedule. In summary, little research has combined both project and operation levels in order to improve construction planning. For real projects, it is necessary to consider these levels simultaneously together in order to comprehensively rehearse the planning involved.

6.5 Using Virtual Prototyping for Motion Simulation

Virtual Prototyping possesses a motion simulation function for both modelling and analysis of plant.. Kinematics performance (velocity, acceleration, position, displacement and rotation) is modelled to verify plant design and identify possible interferences and collisions between various parts of an assembly

(Zorriassatine et al. 2003). Instead of building cost-inefficient physical prototypes, motion simulation can also be used for tolerance analysis so as to provide integration and space requirement tests. A motion model for a crane consists of 3D models and constraints. The 3D models are drawn by CAD which represents parts or assemblies. Constraints include 1) entities between parts or assemblies, such as revolute and slot joints that limit the degrees of freedom of movement of their associated parts or sub-assemblies and 2) capacities, such as velocity, turning ratios and lifting times.

As project and operation levels put different elements into perspective, if a comprehensive approach is desirable to analyse the feasibility of a construction plan effectively, both levels should be taken into consideration at the same time. To simulate the construction process at two levels, VP technology is needed.

6.5.1 The Framwork for Integrated Planning on VP Technology

The framework is optimized and then modified so as to be suitable for bridge projects. The tool can analyse the feasibility of different construction plan scenarios enabling planners to select suitable methods, with validation as the core purpose. The VP system consists of the modules: Design, Database and Operation. The Design Module is used for the design of 3D models and the allocation of resources in construction planning. The Database Module is a data system providing information such as a resource model and constraints for the design module. The Operation Module is a program system for simulating the final-design output to report the results. Fig. 6.1 shows the VP framework of modules.

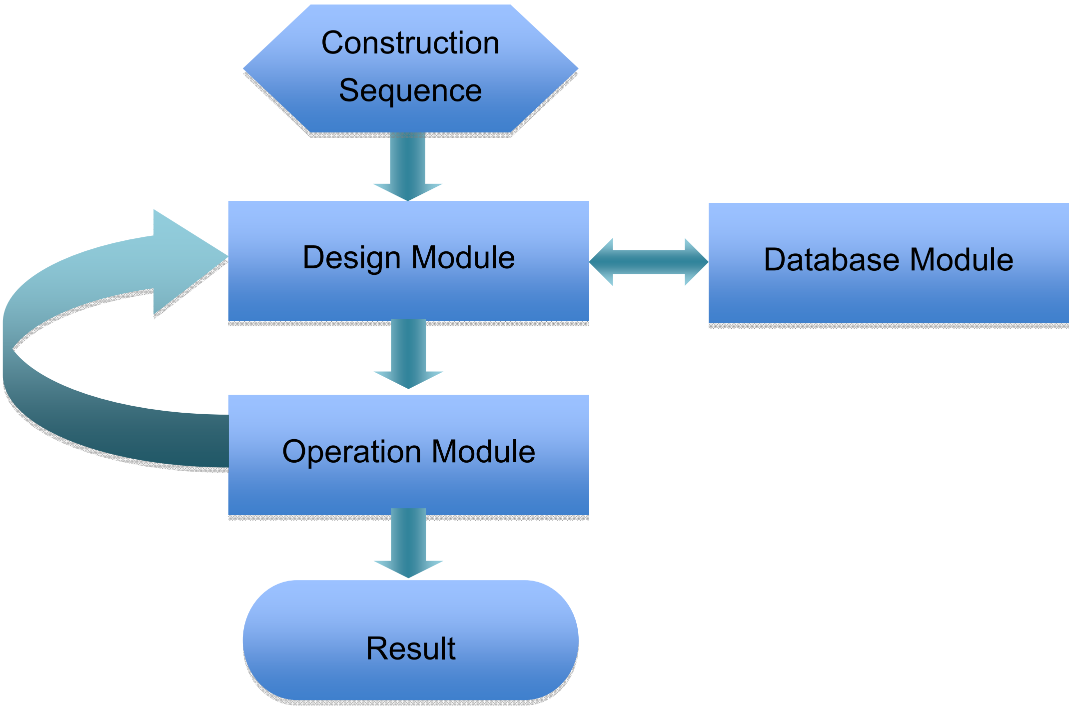


Fig 6.1 The VP module framework

6.5.2 Prototype of Construction Sequence

A construction sequence prototype is defined as the foundation of logical activity. The sequence cannot be changed. One example is Pier Construction (i.e. Pipe Cap Excavation -> Pipe Cap Concreting -> Pier Construction -> Pier Head Construction). A different construction plan should be developed according to a construction sequence prototype.

6.5.3 Proposed-built Model

The proposed-built model is based on a BIM system (i.e. CATIA) which provides the 3D CAD components. In general, BIM systems currently available on the market do not have built-in functions that allow this form of information integration.

6.5.4 A Construction Plant and Equipment Model

The optimum use of construction plant and equipment is critical to a construction design / plan. The construction equipment model is an enhanced plant and equipment-based model. It links the plant and equipment productivity Excel library database together with physical capacity data used in construction planning and construction simulation. It is a 3D-geometry model embedding the specifications of the construction plant and equipment items concerned. This includes such as the actual geometry, turning data and working range radius, and lifting capacity. The construction plant and equipment model simulates real-life working processes (e.g. the crane lifting the steel from the storage area to the final position for installation). If the plan is not feasible (e.g. there is not enough workspace for driving or not enough distance from the target), the problems, based on the specification data, are highlighted by the VP system. The VP system is also able to detect potential collisions between the plant items involved in the operation, as well as the course leading to such collisions.

6.5.5 Construction Plant and Equipment Database

The building of a database is an efficient management approach that enables the storing and capturing of all types of information from construction plant and equipment models and also includes productivity date. All the productivity data acquired from a similar construction project over a two week period and can be computed for virtual prototyping use. The virtual platform simulates the plant and equipment operations to test for any collisions. All the construction plant and equipment models are built and stored in the VP system library installed in the system for future planning use. Different types of plant and equipment as well different types of activities are grouped and classified (Table 6-1). Project planners, based on experience are then able to select suitable plant models from the database and allocate appropriate plant for designated activities when analyzing construction scenarios.

Activities		**Plant**		**Plant Models**
Concreting	←	Tower / Crawler	←	CCH50T, HS873HD, HS855HD, HS841D
Excavating	←	Excavator	←	A316, A900
Lifting	←	Tower / Crawler	←	CCH50T, HS873HD, HS855HD, HS841D
Piling	←	Piling Machine	←	Hydraulic Crawler Drill HD90 Hydraulic Crawler Drill HD180 Pile machine BSP355T Pile machine 325L

Table 6-1 Plant and equipment categories for different activities

6.5.6 Plant and Equipment-resource Allocation

In previous research studies, resources include space, equipment and crews. However, the crew is not as critical a factor in the construction planning of a bridge project as plant and space, as bridge construction is not as labour intensive as a building project, whereas plant is the most critical item affecting the cost and construction duration. In the VP system concerned plant allocation is free to be determined by the construction planner. The duration of each task is generated by computing the amount and type of plant based on productivity. Different construction scenarios can be simulated involving different temporary works proposals and different plant allocations.

6.5.7 Temporary Works Design (i.e. temporary platform)

As stated above in Section 5.8, an FGM-A member indicated that it would be better for construction planning and scheduling to take place at the same time as site-layout planning. In the bridge project, the site work area is on a hill side, The site itself, in effect, is a temporary working platform.

Owing to the fact that there is a limited working area and there is potential for accidents, the design of the site layout (i.e. temporary platform) was a critical planning factor. The proposed-built model (i.e. the set of elements to be constructed, each one a convenient work package. The final bridge is the assembly of these elements.), construction plant and equipment and temporary works design are three key factors influencing construction planning. At the same time, decisions on these three factors, which are variables, have significant effects on each other (Fig. 6.2). These interactive relationships and constraints have been built into the design module.

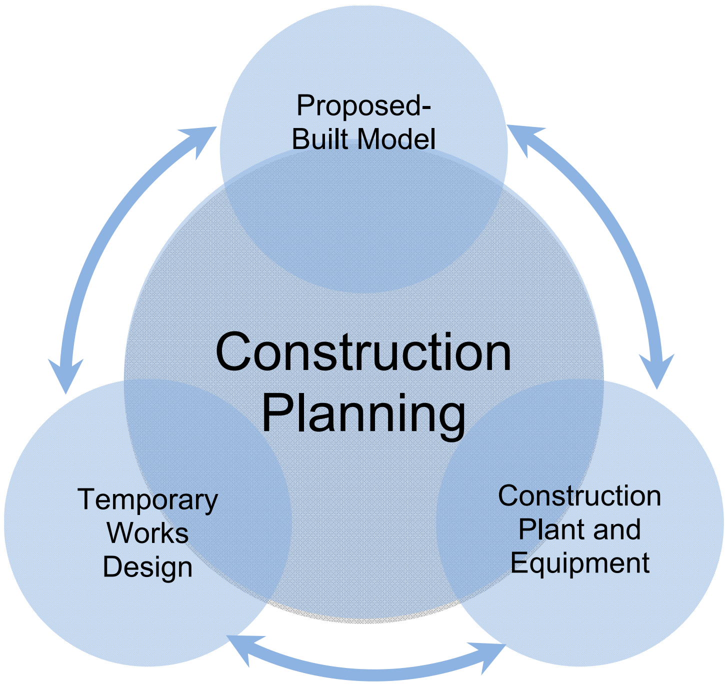


Fig 6.2 The relationships among proposed-built model, temporary works design and construction plant and equipment in construction planning

Parametric 3D modelling is applied to building construction projects worldwide (Huang et al. 2007; Slaughter and Eraso 1997; Sacks et al. 2004). Huang et al (2007), for instance, has applied this form of modelling to temporary work elements and Sacks et al. (2004) have used a parametric 3D model to design precast concrete. These models are based on operations and constraints, with constraints maintained as an integral part of the model geometry during editing.

The temporary works design in the VP system uses a parametric 3D modelling approach and is based on fundamental constraints, user requirements and safety considerations. This model provides a user-friendly platform for sketching and modifying the basic 2D design. Temporary work design has its own design components which are affected by the specification, quantities and plant logistics and locations as well the locations and sizes of the proposed-built model elements.

6.5.8 Collision Detection

A collision detection is a physical clash between 3D elements and simulation helps to identify when collisions will occur and where they occur. The two types of collision are 1) static objects vs. dynamic objects (e.g. plant hitting railings); and 2) dynamic objects vs. dynamic objects (e.g. the activity of an excavator and a crane).

The occurrences of collision relate to the space available. For example, whether a road is wide enough for more than two items of plant to pass is a key factor affecting the scheduling of activities (Fig. 6.3). When space is too limited movement activities are highlighted by VP as a geometric contact when they are about to occur or have actually occurred. The result is generated in the form of data, including the activity time and the name of the two elements involved in the collision.

Fig 6.3 Representation of situation

6.5.9 Possible Results

Possible results of a construction scenario are as follows:

1) Feasibility result (If no collision is detected, the construction scenario is feasible. Otherwise, it is infeasible. As a result, the following clash reports may be generated.)

   a. For a collision detected between a static object and a dynamic object, a clash report providing details of the location within the proposed built model or the temporary work design model, occurrence time and a capture of the virtual occurrence will be generated.

   b. For a collision detected between a dynamic object and another dynamic object, a clash report providing details of the two associated activity tasks, occurrence time and a capture of the virtual occurrence will be generated.

2) A comprehensive construction plan including the design of temporary platform and plant-resource allocation;
3) Quantity of steel for making temporary platforms;
4) Duration of the construction plan;
5) Visualization of the construction process simulation.

6.6 The Planning Process on the VP System

The planning process on the VP system is shown in Fig.6.4.

Step 1: Planning the prototype of construction sequence of the task including start-end time of all activity tasks such as concreting, pouring, fixing rebar etc

Step 2: Designing the temporary platform under the constraints set by the proposed-built model

Step 3: Selecting and assigning the type and numbers of plant items based on the nature of each activity task

Step 4: Validating the route and working platform to decide whether there is enough working area for the selected plant and the work space (if it fails, go back to step 2 or 3)

Step 5: Validating absence of activity clashes between plant (if it fails, go back to step 2 or 3)

Step 6: Generation of the results

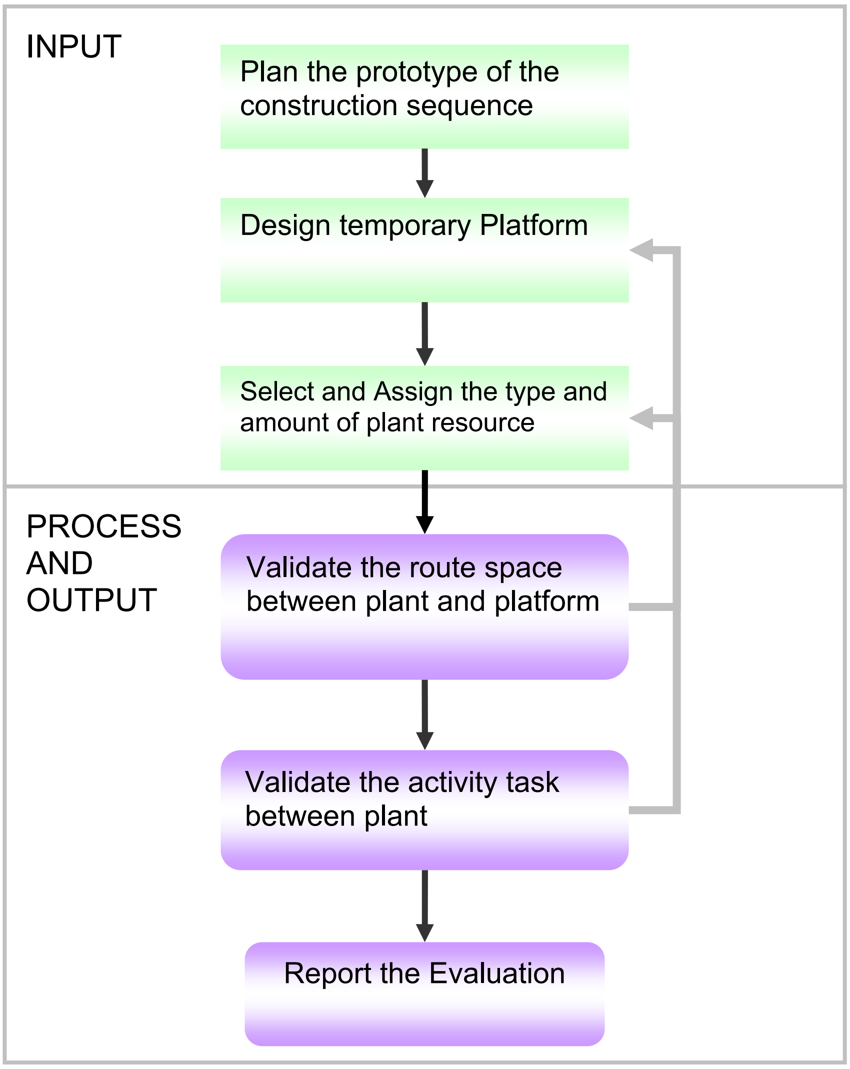


Fig 6.4 The planning process on the VP system

6.7 Summary

In this chapter, the process of modifying the integrated planning framework enable resource analysis to suit the needs of bridge projects is presented. The characteristics of bridge projects are described to identify the critical issues relating to bridge project VP based on the literature and FMG-B feedback. The VP motion simulation was used to optimize the plant motion in the framework. The next chapter describes how the framework can be applied to a bridge project.

CHAPTER 7 CASE STUDY ON BRIDGE PROJECT

7.1 Introduction

In this chapter, a real-life case study is presented which demonstrates the use of VP with temporary platform design and plant allocation for generating different construction scenarios to improve the construction plan. The Focus Group Meeting (Team B) was held and their feedback regarding this case study was collected.

7.2 Case Study

The case study involved the widening of a section of Ting Kau Viaduct, which is a part of the Tuen Mun Road linking Tuen Mun and Kowloon, Hong Kong. The total length of the road is 15 km and it has been in service for more than 30 years, having a long history of traffic congestion and accidents. The road was designed and constructed in the mid-1970s and there was a need to raise the road to current standards as far as practicable. In addition, reconstructing the road was planned to minimize repair works, traffic congestion and accidents, and therefore create less disturbance for road users.

The main scope of work included widening sections of the existing carriageways and vehicle bridges and highway structures, including the Tsing Lung Tau Bridge, Telford Bridge, Ting Kau Viaduct and Yau Kom Tau Bridge. The work also included widening the eastern end of the Sham Tseng Viaduct eastbound carriageway to meet current expressway standards, with the associated provision of hard-shoulders and verges.

The work of widening the section of Ting Kau Viaduct included construction of viaduct foundations, piers, deck and finishes. Ting Kau Viaduct is supported by numerous piers placed on a hillside, and twenty-eight new piers required for the widening of the Tuen Mun road. The work involved complex site topography, localized site formation work, foundation, superstructure and stitching work to the existing road network.

The project planners encountered several types of problem relating to construction planning and constructability, including potential risks to road users in the construction area, and a number of key concerns were incorporated at this stage, including site safety, site access, temporary work design, cranes and other plant deployment. A central issue for the project planners concerned the working platform to be used in the construction process. This involved choosing one of three different working platform designs. However, the choice was not easy, due to:

- Difficulties in imagining the site environment.
- Difficulties in determining the best platform for foundation and pier construction.
- Difficulties in estimating the maximum number of resources for each of the different platform designs.

7.3 Building the Virtual Terrain Contours, Existing Viaduct and Proposed Widening of Viaduct Structures

To increase the precision of the results, the researcher obtained topographical survey data of the project site from the land surveyors involved. This included terrain contours and details of the existing Tin Kau Viaduct which were built into a 3D model. The 3D virtual terrain contours provided a clear and detailed view for the project planners, allowing them to visualize the relationship between the terrain contours and the existing viaduct and to predict safety issues and potential accidents during construction. The proposed widening of the viaduct structure was modelled to include geometric configurations after construction, based on the 2D drawings (Fig. 7.1).

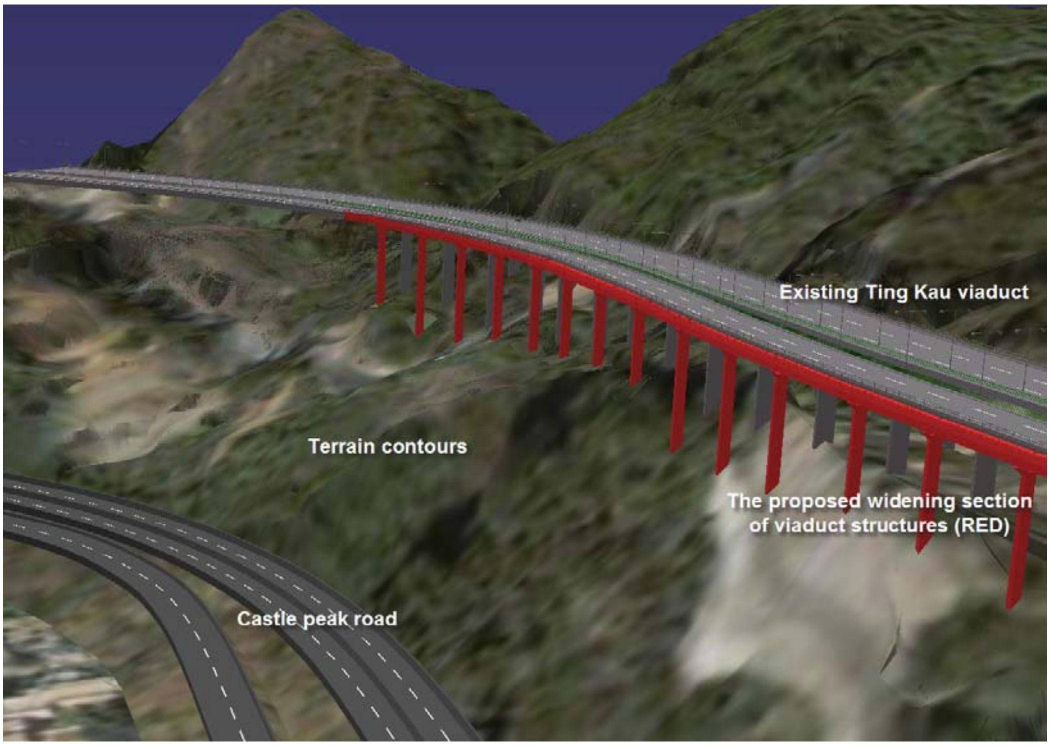


Fig 7.1 Virtual terrain contours, existing viaduct, Castle Peak Road and the proposed widened section of viaduct structures

7.4 Construction Planning

The construction planning involved temporary work design and resource allocation. Through the constraints with the proposed-built model, the precision and reliability of the temporary work design can be increased. The project planner assigned and allocated different numbers of construction plant to the three alternative working platform designs. The different feasible construction planning processes were simulated adopting the construction sequence shown in Table 7-1.

Order*	Activity	Duration
1	Haul Road Construction	13 days
2	Timber Platform Erection	14 days
3	Minipile for Steel Platform Driving	27 days
4	Footing for Steel Platform Construction	10 days
5	Timber Platform Removal	7 days
6	Steel Platform Removal	21 days
7	Pre-bored H-Pile Works	12 days
8	Pipepile Wall Driving	20 days
9	Pile Cap Excavation	7 days
10	Pile Cap Concreting	7 days
11	Pier Construction	24 days
12	Pier Head Construction	12 days
13	Launching of Precast Beam**	2 days
14	Deck Construction	7 days

* Construction sequence is set in an order from 1 to 14.

**Precast beam should be launched after two piles of head construction.

Table 7-1 The duration of each activity for one pair of piers

7.5 Construction Scenarios for Temporary Work Design

The choice of platform design was influenced by two main considerations:

- The haul road - an access road from Castle Peak Road to the construction site for construction plant and equipment to be transported.
- The platform itself.

7.5.1 The Haul Road

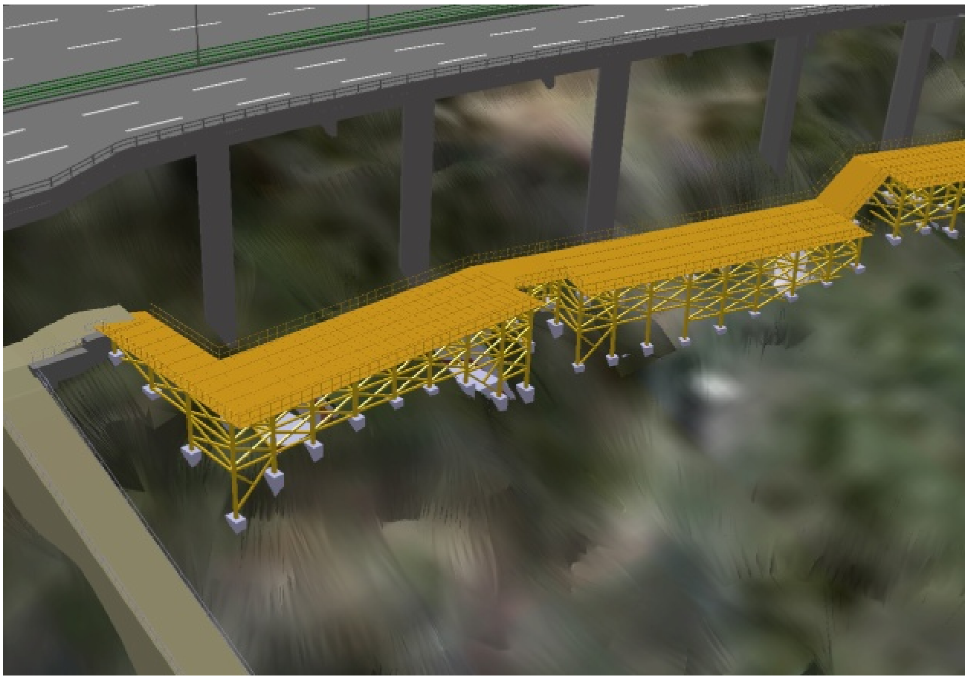
Most of the critical construction work was situated under the existing viaduct and on the hillside. However, the hillside was not a suitable platform for workers and construction plant and equipment which had to be driven from Castle Peak Road to the proposed construction site along a haul road (Fig. 7.2). The essential requirements of the haul road were that the slope was not greater than 1:10 and had a minimum width of 5m. These two requirements were built into the haul road model.

Fig 7.2 The haul road from Castle Peak road to construction site

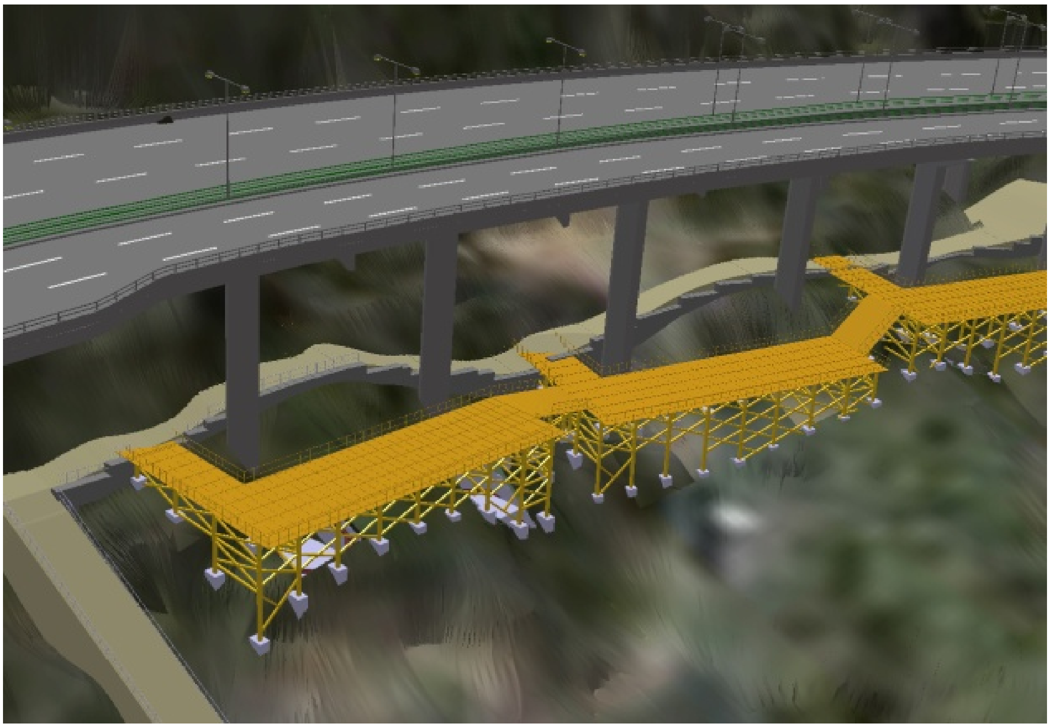
7.5.2 The Platform

The function of the steel platform was to provide a working space from which the piling plant could operate. It would have been difficult for the project planner to confirm a platform design because of its importance to the success of the project. Using the parametric 3D model however, the design of the steel platform could be drawn and modified easily and quickly. The platform safety designs features remained fixed throughout the modelling process, and the platform railings were generated automatically in each of the three model designs produced by the researcher. Approximately forty man-days were taken to model the haul road and the platform. The three different designs of steel platform are shown in Fig. 7.3. These comprised:

(Design A)



(Design B)



(Design C)

Fig 7.3 Three different scenarios of steel platform

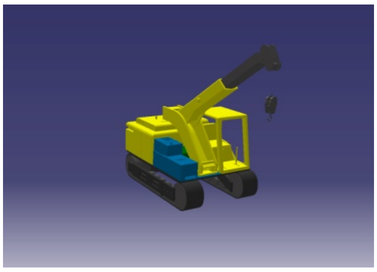
Design A - Each platform overlapped two piers, with the entrance connected to the haul road.

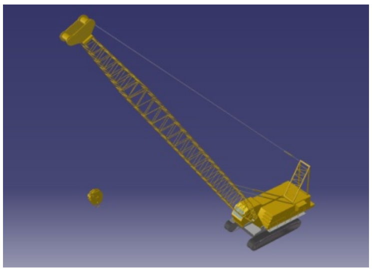
Design B - Each platform fully overlapped all piers but with only one entrance connected to the haul road.

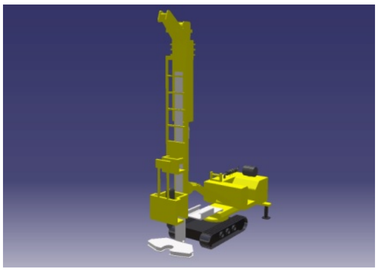
Design C - Each platform was similar to that of design B but each pair of piers provided one entrance connected to the haul road.

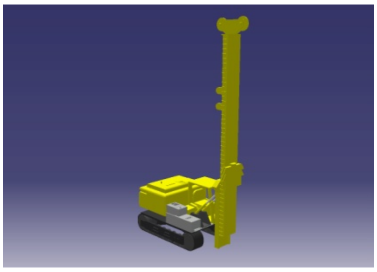
7.6 Construction Plant and Equipment Database

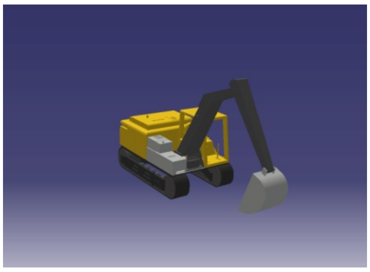
The major models of construction plant and equipment (Fig. 7.4) were built in detail, including the external dimensions, working radii, moving and working space requirements and lifting capacity. For example, a 3D crawler crane model was developed which included its external dimensions based on the specifications, degrees of low and high limit of turning radius, rear-end swing and working radius (Fig. 7.5). The various lifting capacities were based on the working radius. Modelling all the construction plant and equipment was a time-consuming process involving approximately 160 man-days spent on creating a single model and the embedded specifications. It should be noted, however, that, once built, the models of all the construction plant and equipment involved would be instantly available for future reuse when needed.


Crawler Crane

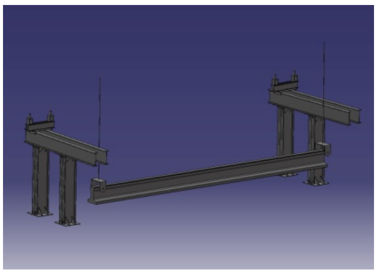

Crawler Crane


Hydraulic Crawler Drill


Pile driving machine 325L


Excavator


Concrete Mixer


Steel Gantry


Crane Lorry


Lorry

Fig 7.4 The major models of construction plant and equipment

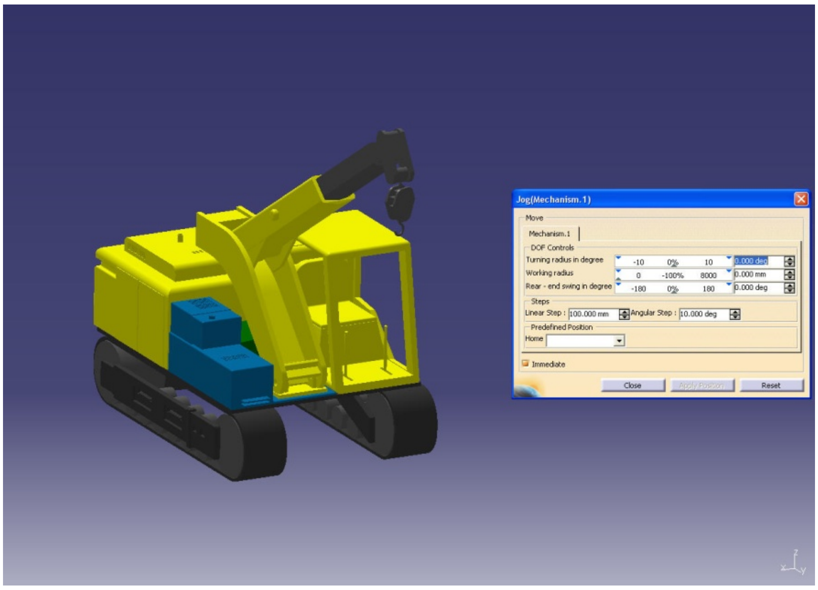


Fig 7.5 The crawler crane CCH50T with embedded specification

7.7 Allocation of Construction Plant and Equipment Model

The construction plant and equipment model was selected and assigned to different activities in the construction sequence (Table 7-2) based on the constraints of the proposed-built model. Eight types of construction plant and equipment and two types of platform were involved. For example, the construction plant for the pier construction activity consisted only of a single Crawler Crane HS873HD as one of the constraints defined that a crawler crane should be able to lift temporary steel formwork for pier concreting. The user could assign varying numbers of construction plant and equipment items to the three platform designs. Based on different designs and different resource allocations, the system was used to simulate the construction plans.

Order	Activity	Construction Equipment	Other Resources
1	Haul Road Construction	Lorry	a large number of crew
2	Timber Platform Erection	Lorry	a large number of crew
3	Minipile for Steel Platform Driving	Crawler Crane CCH50T Hydraulic Crawler Drill HD90	
4	Footing for Steel Platform Construction	Crawler Crane CCH50T	
5	Timber Platform Removal	Lorry	a large number of crew
6	Steel Platform Erection	Crawler Crane CCH50T	
7	Pre-bored H-Pile Works	Pile driving machine 325L Crawler Crane HS873HD	
8	Pipepile Wall Driving	Pile driving machine 325L Crawler Crane HS873HD	
9	Pile Cap Excavation	Crawler Crane CCH50T Excavator Lorry	
10	Pile Cap Concreting	Crawler Crane CCH50T Concrete Mixer	
11	Pier Construction	Crawler Crane HS873HD Concrete Mixer	Steel formwork
12	Pier Head Construction	Crawler Crane HS873HD Concrete Mixer	Steel formwork
13	Launching of Precast Beam	Steel Gantry	
14	Deck Construction	Crane Lorry	

Table 7-2 Different construction plant and equipment assigned to different activities

7.8 Collision Analysis

The two types of collision analysis in the VP system were to detect and highlight any potential collisions between construction plant and equipment and the virtual environment such as platform railings and the haul road in the simulation and between the activities of different plant items. The clash report highlighted the associated activities and models together with the occurrence time.

7.9 Site Validation

The site validation was adopted again in this case study. The steps of the case study of the building project were the same as referenced in section 5.7. The difference between the former one and the current case is in the site validation duration, which is longer (i.e. 4 months). The reason was that the project planner did not have enough information and data for this study and he needed more time for collection. There were many uncertain factors such as which plant to use and the suitable flexible design of the steel platform. Therefore, more time was necessary to re-design the VP system.

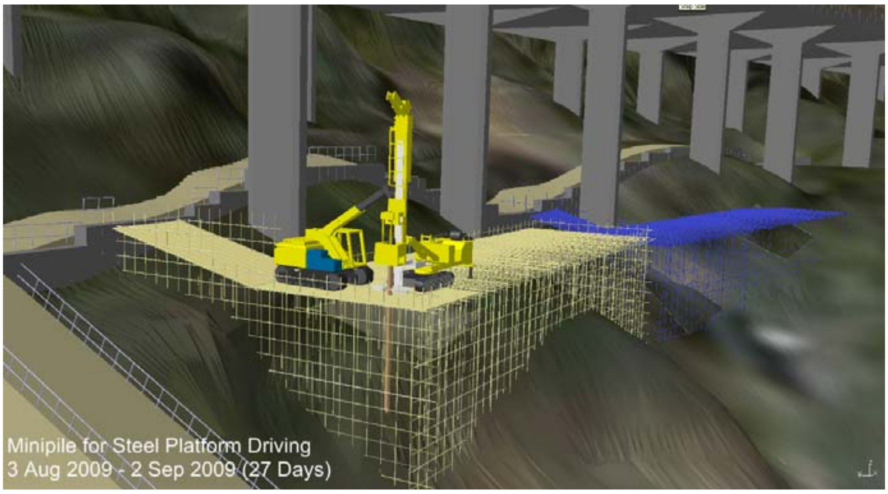
7.10 Overall Results

For design A, the system identified clashes between the crawler crane HS873HD and the existing viaduct as the crawler crane HS873HD could not be driven from one platform to the next due to limitations in headroom. Parts of the crawler crane had to be dismantled and reassembled after the crawler crane had been driven to the next platform, a process which would take 30 days. Other types of plant had no such problems.

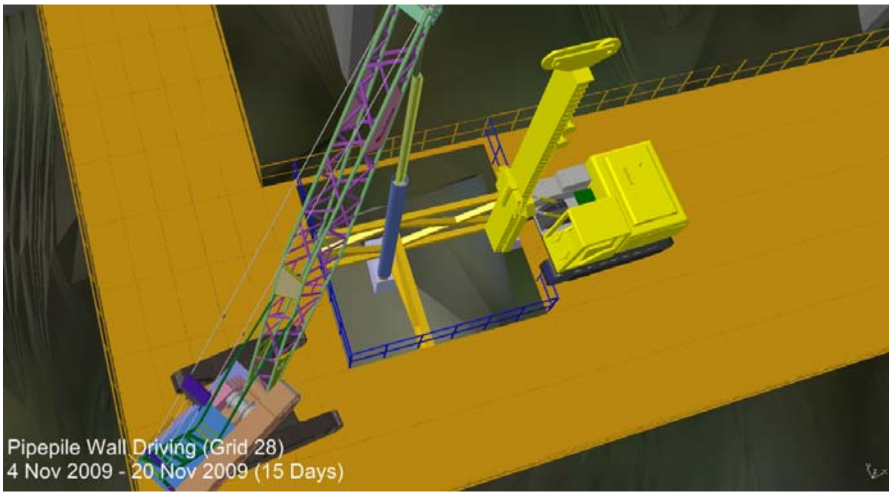
In design B, there was one access road for transportation. Pier construction therefore would be undertaken one by one. Hence, one item of plant was the maximum that could be allocated. The reassembly time of the crawler crane HS873HD in design A was eliminated as the crane did not need to pass along the haul road from one platform to another. Therefore, the planner tried to enlarge the platform size to make sufficient room for two-way transportation. These results were of significant importance.

In design C, each platform was connected to the haul road and the next steel platform. The crawler crane could move across the connection between two steel platforms. Once again, dismantling and reassembly of the crawler crane HS873HD was eliminated. Design C provided the best transportation model for the construction plant and equipment.

Realistic graphical simulations (Fig. 7.6) were generated for visualization through the VP system and validated by the construction planners as some activities could not be easily visualized in any other way. The planners and engineers spent some time studying the visualization to try to identify activities that had not been considered so far. The professionals also discussed how the most benefit could be obtained from the VP simulation technique. The quantity of steel for making the different platforms, the number of plant items and the project duration were generated for planners to investigate different scenarios and to then select the optimal construction plan. The planners then used the data to process and discuss other analyses.



(a) Minipile for Steel Platform Driving



(b) Pipepile Wall Driving

(c) Pier Construction

(d) Launching of Precast Beam

Fig 7.6 Snapshots of the construction simulation

7.11 Feedback

Feedback from the Focus Group Meeting (Team B) indicated as the case study shows, that VP, in conjunction with the project planners' real-life experience, can be useful for testing the feasibility of the platform alternatives. VP provides the functions to 1) analyse the allocation of plant items to prevent mistakes between working platform design, plant numbers and start-finish times of activities; 2) speed up planning times with the use of a plant database; 3) project the quantity of the materials involved in the temporary works; 4) generate the duration of the construction work; 5) help project planners to select a construction scenario by testing different alternatives.

However, a limitation of the solution framework is that the modelling of construction plant and equipment is very time-consuming. To make an efficient contribution, a comprehensive plant database needs to be already available.

Another limitation of the VP system in bridge planning is that it falls short of identifying the optimal construction plan. When attempting to identify the optimal construction plan, project duration needs to be taken into account in addition to the cost of the working platform and plant. Nevertheless, a shorter duration does not necessarily imply a better construction plan. For instance, although the VP system can analyse different construction scenarios relating to the working platform and plant, it overlooks the deployment of workers. For the sake of social responsibility, a construction plan needs to allow different types of workers (i.e. for formwork, concreting, fixing rebar) to work every day.

7.12 Summary

The case study demonstrates a VP application which enables users to validate the design of working platforms with different resources allocated. The VP system can simulate construction scenarios to predict collisions between construction plant and equipment and construction elements. It can also help the project planners to identify an optimal construction plan. However, the VP system possesses the limitation of being very time consuming in plant model building and it falls short of identifying the optimal construction plan.

CHAPTER 8 CONCLUSIONS

8.1 Introduction

The research objectives of the study are summarized, followed by the conclusions reached and the objectives were met. The limitations of the scope of the work are described and suggestions are made for useful further research.

8.2 Review of the Research Objectives

The opening chapter of this thesis outlines the background of construction industry processes where improvement is thought possible. The aim of this research was to develop an integrated planning solution for optimizing construction planning and scheduling activities taking account of resource needs using VP techniques. The objectives were: 1) to investigate the existing methods used for improving and optimizing in both the research and industry domains; 2) to identify the nature of the resource analysis techniques needed to conduct construction planning and scheduling; 3) to design a research methodology, in the light of objective 1 and 2, that would be applicable to real case projects; 4) to develop a framework for integrated planning using VP technology; 5) to test the usefulness of the framework on real case studies by assisting the construction planners to improve plan accuracies through simulations of actual progress in advance of actual construction.

Regarding the first objective, most of the existing methods used are described in Chapter 2. All the methods have their advantages and disadvantages. However, no existing method is sufficiently comprehensive to integrate resource analysis in construction planning.

Regarding the second objective, the resource analyses of planning importance were identified through focus group meetings and are described in Chapter 4. The key resource factors include space, tower crane, crews and quantities of these resources.

The third objective, described in detail in Chapter 3, related to design of research methodology. In order to obtain practical data and increase VP applicability to the industry, action research was chosen as the core of the research, to enable close collaboration with the construction industry. The literature review, focus group meetings, case studies and site validation were employed into the action research to enhance the research result.

Regarding the fourth objective, the core of the research preparation was to develop the framework for integrated planning using VP technology as shown in Chapters 4 and 6. In order to develop the framework, focus group meetings were held and case studies conducted to build and verify the framework. Chapter 5 and Chapter 7 demonstrate the technology in action for optimizing the construction planning and scheduling of a building project and a bridge project respectively.

Through the case study implementations, the approach shown that VP technology can help to plan more accurately and to rehearse construction with a visualized simulation of actual construction activity leading to the achieving of the fifth objective. The results of building project and bridge project action research case studies are given in Chapter 5 and Chapter 7.

8.3 Contributions of the Research Study

The main contribution of this research study is the development of a solution framework enabling optimized construction planning and scheduling for building and bridge projects. The purpose of using VP technology for construction simulation is to assist project planners to better understand the construction process and predict potential problems. The first building project case study demonstrated that the VP system enabled the users to validate a proposed construction plan and schedule. In particular it showed that the VP system can also be used for analyzing the use of access roads, tower cranes and space resources and hence prevent the possibility of plant collisions and identify other potential problems common during the construction. It is thus shown that the use of VP can reduce the chance of delays in construction.

The second case study, a bridge project, demonstrated an application in which the VP system enabled the user to test alternative working platform designs. The appropriate resources for each were identified. It was thus shown that VP can be used to simulate construction scenarios to discover where and when clashes for workspace during the construction of structural elements and collisions for plant might occur. VP can also help the project planners identify the optimal construction plan.

Several other contributions have been in this research are as follows:

- **Utilization of the characteristics of Building Information Modelling (BIM) to embed specification and productivity data in a plant models**

  One BIM characteristic is its ability to store large amounts of information in its models. This research utilized this characteristic to store specifications and productivity data in plant models. The specifications for a crane, for example, included the actual geometry, turning circles, working radius ranges and lifting capacity at different ranges. The VP system utilized these specifications when simulating real-life plant working processes and productivity data to verify and then adjust resource allocation.

- **Decomposition of BIM models for scheduling and a detailed simulation**

  The ability to carry out simulations is a key feature of VP technology. The decomposition of the 3D product model into a chosen set of parts for later assembly was a precondition of simulation. The VP system successfully utilized the BIM models for this process.

- **Construction plant and equipment database**

  The Construction plant and equipment database was developed for future planning use. Building a database was an efficient approach for storing and capturing all types of information relevant to planning and costing and productivity. In order to make an efficient contribution, a comprehensive database for all types of plant items needed to be available. A complete database could help to reduce much of the modelling time and the collection of productivity data. Once completed, the plant model and its productivity data were reusable on other projects.

- **Development of a relationships model for the proposed-built model, the site layout plan (i.e. temporary works design) and plant and equipment-resource allocation in construction planning**

  The proposed-built model, construction plant and equipment and temporary work design were identified as three key factors influencing the construction planning for the bridge project. These three factors, which are variables, have simultaneous significant effects on each other. The relationships and constraints between the three factors were built into the design module. The proposed-built model exerts constraints on the temporary work design.

- **Combination of the project level and operational level in construction planning and scheduling**

  The VP system takes the project level and the site operational level into consideration at the same time in order to make effective analysis of the feasibility of the construction plan. To achieve this aim, construction plant was analysed using the VP unitization of plant motion analysis.

- **Enablement of resource analysis in construction planning and scheduling**

  The resource analysis developed in this research, as previously indicted, is for the optimization of construction planning. The resource analysis involves space, plant (i.e. tower crane) and crew. Based on real productivity data, the VP system checked the planned duration of tower crane activities and then adjusted the activity duration. It ensured that the proposed duration was sufficient for different activities to have access to a tower crane. The space resource was involved in storing material and plant, and providing 3D working space over time. The VP system determined the number of trucks based upon the required quantity of reinforcement and façade units for the 6-day cycle and then computed the storage area needed for the reinforcement and façade units.

- **The adoption of site validation for the research method**

  In order to improve the development efficiency of this study and obtain a more usable and practical solution for the planner, site validation which is a new research method and process, was used. The aim is for the researcher to work full-time in the construction office with planners and engineers during the whole development (two to four months). Through working together, the researcher can obtain immediately 1) the most updated information, 2) the newest and clearest requirement, 3) test and validate the tools to be used, 4) get their feedback and 5) provide a platform to test various construction plans.

- **Provision of a VP system platform for the planners to test the construction plans (optimization process)**

  The VP system provides a platform for planners to perform the construction planning for visualization in a virtual environment and to test the feasibility of the construction plan. The planner can understand the planning problems / mistakes and deficiencies based on planning mistakes or planning errors such as activity conflicts, detection of the plant and equipment clashes, all of which are gained from the analysis of the VP result. The planner can understand the planning problems / mistakes and deficiency. The planner then modifies the plan accordingly. They are then plan again and re-plan until the optimal construction plan is identified.

8.4 Limitations of the Research Study

The contributions of this research are as described above, however, the integrated planning solution is limited in the following ways.

Modelling construction plant and equipment is a time-consuming process. The construction period is usually tight. Time was not saved during the case study presented and the modelling cost was more than could normally be afforded. However, a comprehensive plant database was made available. In addition, a complete database would help to reduce modelling time and the collection time of productivity data. Once completed and verified, the resource model and the productivity data would be available for other projects.

Another limitation of the planning solution framework is that it falls short of identifying the optimal construction plan. When attempting to identify the optimal construction plan, the project duration needs to be taken into account in addition to the cost of the working platform and plant. Nevertheless, it needs to realised that a shorter duration does not necessarily imply a better construction plan. For instance, although the VP system can analyse different construction scenarios relating to the working platform and plant, it overlooks the scheduling of the workers. For the sake of social responsibility, a construction plan needs to allow the different trades (i.e. formwork, concreting, fixing rebar) to work every day.

8.5 Recommendations for Future Research

This research investigated methods that enable core graphical technologies to portray models of construction processes in a dynamic, smooth, and continuous 3D virtual world. The work, while significantly advancing the state-of-the-art activity, has revealed several other interesting research issues that would benefit from future research.

Feedback from focus group members indicated that a fully automated platform design process was desirable, opening the way for further research into the use of VP for project planning. VP does provide a platform to test the performance of various plans but to automatically select the optimum plan needs research into an approach involving artificial intelligence methods.

Secondly, future research on planning optimization should take social responsibility into account. A construction plan needs to allow the different types of workers (i.e. formwork, concreting, fixing rebar) to work every day. Indeed, if the plan fails to address this issue, a sub-contractor may not accept the jobs offered. Although the sub-contractor does not have a choice, the main contractor should be socially responsible, and not focus only on profit.

Lastly, most researchers have focused on how to improve the IT optimization technology. Advancing the development of the construction industry, however, is more important than this. Researchers not only have to improve the technology but also make it suit the needs of the users. Future research should be led by construction planners' needs to provide the appropriate technology. This is the best way of advancing technological progress.

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