THE UTILIZATION OF BUILDING INFORMATION MODELING IN COMPUTER-CONTROLLED AUTOMATIC CONSTRUCTION: CASE STUDY OF A SIX-ROOM WOODEN HOUSE

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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May 2016

Major Subject: Construction Management

ABSTRACT

In the current context, Building Information Modeling (BIM) is belatedly providing the construction industry with a tool to reach higher levels of efficiency, quality and convenience. However, human errors in both management and construction job site control may cause a construction project to go over budget or behind schedule. Lastly, a construction project requires the collaboration of various parties to achieve the end goals of the various stakeholders. BIM provides one method of integrating the whole process of sharing information between those parties. Extensions to the current BIM methods may allow machines, such as construction robots to take over some of the human tasks. The aim of this study is to study future methods to reduce the human effort in construction and to improve the cost efficiency and quality for construction projects.

In this thesis to look to integrate the construction processes of design, manufacture, shipment and installation and using data extracted from a BIM model, a conceptual computer-controlled, automatic construction process is developed for a pseudo robot. The pseudo robot is merely a development tool to look at the development of the conceptual phases for a real robot. Meanwhile, following the Plan-Do-Check-Action (PDCA) management cycle, the workflow of the process is designed in pseudo-code. A case study of a six-room wooden house is used to illustrate the function of the automatic construction system and to verify that which information can be provided by BIM.

Location control is identified in the study as the key criterion for attempting robotic construction. An object positioning solution of using a laser technique is suggested from this research. The results show that the program provides adequate information to allow the completion of the construction process. A two-level method is developed for accurate positioning of building components. Further research may focus on more complicated and special projects, more effective and accurate sensing and tracking technology.

DEDICATION

To my family and friends.

ACKNOWLEDGEMENTS

I would like to thank my committee chair, Dr. Nichols for his help and patience in guiding my research. Also I appreciate the guidance and support throughout the whole process from Dr. Glowacki and Assistant Dean Feigenbaum. I express my gratitude as I would not have accomplished this study without them.

Thanks also to my friends and classmates and the department faculty and staff.

Finally, thanks my father, my mother and my girlfriend for their support and company.

NOMENCLATURE

AEC industry	Architecture, Engineering and Construction industry
AI	Artificially Intelligent Systems
BIM	Building Information Modeling
GIS and WAN	Geographical Information System and Wide Area Network
GPS	Global Positioning System
GUID	Globally Unique Identifier
IFB	Invitation for Bid
IFC	Industry Foundation Classes
ifcXML	Industry Foundation Classes Xml File
LIDAR	Light Detection and Ranging
PDCA	Plan-Do-Check-Action Management Cycle
RFID	Radio-frequency Identification
RTK	Real Time Kinematic
STEP	Standard for the Exchange of Product model data
XML	Extensible Markup Language

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CHAPTER I

INTRODUCTION

Background

A demand exists to more rapid development of construction, often driven by the demands of the investment cycle (Hartford, 2005). Building projects become more complex as modern infrastructure related to communication and energy management are incorporated into the fabric of the structure. Project managers find it is time-consuming to complete even relatively simple building projects, such as dormitories and residential houses, given the current technological and legal demands on the industry. The ultimate point is to maximize returns (Smith, 1976).

Smith (1976) in his seminal work on the *Wealth of Nations* shows the basis of the simple economic model that controls all human activity of this form. Aibinu and Venkatesh (2013) note that common construction activities such as material procurement, cost analysis, documents preparation, and monitoring of the construction process and cash flow are organized by project managers. Leung, Mak, and Lee (2008) hold the opinion that construction communication efficiency is a significant concern where studies show that nearly eighty percent of the project information has not been passed down through the hierarchy from the construction management team to the site workers. The point is to maximize profit and the idea is to organize work flow and delivery methods to maximize all returns.

Building Information Modeling (BIM) makes the communication of important design and construction data easier and more efficient (Basu, 2015; Dossick & Neff, 2009). This is the theory, however the reality is somewhat different as one takes simple architectural models and attempts to make engineering models from the architectural models, (Nichols, 2011). Architectural models are not designed to be air tight and connected which is a requirement for FE models and leads to a considerable difficulty in translating from one system to the other.

Flyvbjerg (2011) suggests that it is difficult for the project participants to accomplish their work efficiently and to deliver the project within budget and on time. The simplest items to observe are time management controls, rework and poor productivity of workers. Ng, Skitmore, Lam, and Poon (2004) stated that up to forty percent of the cost of construction projects is related to the labor on the job site, however most of the work is poorly controlled, which is one of the key indicators to using subcontractors to provide an economic incentive to control costs.

Grau, Caldas, Haas, Goodrum, and Gong (2009) note that construction's labor productivity had a 0.72% annual decline rate from 1964 to 2000. There may be many reasons for such an observed decline including:

- Aging of the construction workforce
- Movement of workers from blue collar to white collar jobs, creating a brain drain in the construction industry
- Increased skill required to install more complex systems without adequate training
- Cost pressures

Ballard (2000) stated that over fifty percent of construction site work has not been finished on time when compared to the project schedule, which indicates one of three things:

- Inadequate attention was given to the preparation of the schedule
- An inadequate budget was provided and the workers are taking the blame
- Low quality workforce

As a follow on, additional constraints, such as a builder's ability or technological insufficiency, also lead to conflicts in user expectations and building execution. Josephson and Hammarlund (1999) show that more than 12.4% of construction cost involves the reconstruction of defective building components. In the end this is about risk management, the subcontractor gambles essentially on the minimum quality of work to achieve the allowable budget, as with all gambling there are losses.

The key question is whether this accepted risk transfer model is most economically efficient or whether alternative methods are required for the modern world. Looking at it perversely, I want a Picasso and I am going to pay minimum wages to a painter to get one.

Some research work has been dedicated to reducing the human effort in construction industry, akin to robots in factories. Early in 1970s, Scott developed a computer program which can generate construction plans for robots to complete simple constructions (Fahlman, 1974). In recent studies, quad-rotor helicopters are used to complete works such as the pickup, transport and assembly for construction (Lindsey, Mellinger, & Kumar, 2012).

Pheng and Hui (1999) observe that a growing concern exists that the productivity of the construction industry is not as high as other industries. Unlike other industries, such as electronic manufacturing, automobile manufacturing, and computer technology, where the entire manufacturing process is executed efficiently and automatically, the construction industry has had difficulties in adopting new techniques that have greatly enhanced performance in other industries. In essence, the level of automation of these industries is higher than in the construction industry for a multitude of reasons, but the key reason is a lack of robotic construction, poor planning and work on the site instead of the factory. All are signs of an old fragmented industry with a low entry cost and a lousy cost control structure.

Hwang and Liu (2010) observe that in the past few decades, however, the construction industry has been trying to introduce some degree of automated construction process control. The industry has developed various types of data communication systems for the application of building modeling. The complexity of a construction project often makes it a time consuming activity for human managers, who can take days or weeks to solve difficult issues. There is limited research that relates to the automation of a computer-controlled management in the construction industry as opposed to other industries. Questions also remain about how to utilize advanced management tool into a modern construction management team based on effective building information modeling in order to control the workflow of the construction process.

Scheduling efficiency and accuracy is limited both by building models and construction technology. With the development of BIM and information technology, automatic construction scheduling may also be more feasible, especially since BIM is able to provide object based information models instead of 2D geometric drawings.

This chapter develops the objectives of the research to consider the development of techniques to provide for the use of robots in construction.

Aims and Objectives

The study aims are twofold:

1. to look at the use of a computer program to control the construction team and management of a six-room wooden house
2. to provide an example of a computer controlled construction project with computer management instead of human management

The selected building provides a simple example for all types of construction and should not be considered as anything beyond a simple case study for the purposes of this research. This research will look to develop the concept of a single Deming cycle for use in the building of a home efficiently.

The main objectives of this thesis are:

- To develop the conceptual PDCA cycle to construct the house using BIM
- Generate a computer model of the controlled construction procedure

Hypotheses

The hypotheses of this research are:

- The construction processes can be defined and recorded by a newly developed computer program that utilizes Building Information Modeling
- The construction process can be presented in a computer language so that it is possible to perform construction under the management of computer software.

Limitations

This research is still in the conceptual stage and the case study used in this thesis is relatively simple. The research limitations are

- presenting the feasibility of building a few components in a six-room wooded house. Its applicability to other construction projects, such as commercial projects, is unknown
- Only a simple part of the building structure is applied in the case study
- The mechanism and description of the robots that can apply the construction plan is not discussed
- There are many kinds of components in a construction project classified by the method of construction such as precast or pre-manufactured object, cast in place, or assembled on site. In this research, only components that do not need to be rebuilt, such as precast components, will be discussed.

Significance

Chu, Jung, Lim, and Hong (2013) comment on the aging of the population in some of the developed and developing countries resulting in the population for future construction labor shrinking. Safety on the construction site is a motivation for automatic construction.

Many construction projects are over budget, behind schedule or have inferior quality. This research describes an integrated system that utilizes present technology. More advanced computer programs or systems can also be developed in the future. An example of integrating the design, supply chain and site management can provide an idea of how future construction will be based on the newly born information technology and robot technology.

CHAPTER II

LITERATURE REVIEW

Introduction

This literature review considers the development of modern construction methods. The following sections are included in this literature review:

- Human Interfaces
- Building Information Modeling (BIM)
- Industry Foundation Classes (IFC) and GUID
- BIM based construction techniques
- PDCA cycle
- Pseudo code languages
- Construction positioning and tracking technology
- Robot construction technology

Human Interfaces

The human brain is limited in managing large and complex construction projects, due to the complexity of major undertakings. Techniques have been developed in the last century to control the construction process as the complexity of the projects has increased with increasing urbanization. The key question is cramming more people into less space and doing it efficiently. Smith (1976) in his classic text has pointed to the inevitable nature of increasing wealth driving some locations on earth to become economic singularity points taking the standard definition of a singularity as one divided by zero (Borowski & Borwein, 1989). The economic value of this land places a burden on the construction industry to effectively and economically support the construction at these locations and to do it efficiently. At a time when economic transactions times are measured in milliseconds, a construction program timed in weeks and months is a akin to a dinosaur based transport system.

Winston and Horn (1989) provide the basic outline for the development of artificially intelligent systems. The AI system provides a basic tool to ultimately replace the project manager in the work force. The key question is why this system change has not occurred as it has occurred in other industries.

With the development of building information modeling (BIM), people now have a simple method to control some of the data information for every period of a project. It remains to be demonstrated, however, that the computer can utilize the data from BIM automatically in order to control the construction process. This research will focus on the use of BIM to manage fully the construction process in PDCA wheel.

This literature review surveys previous studies related to the development of automatic construction. Information technologies such as Building Information Modeling (BIM), which is the fundamental tool used in this research, sensing and tracking of cargos, data sharing and communication, and robotic techniques may allow computer-controlled construction become a reality. Also, Plan-Do-Check-Action (PDCA) cycle, a management method developed by Deming is applied and presented to develop the idea and process of automatic construction system. The key question is the transition from human to machine control.

BIM

Fu, Aouad, Lee, Mashall-Ponting, and Wu (2006) observe that building information modeling (BIM) is object-based information sharing system that users can use to access the information about a construction project. BIM has been used as an essential tool in the AEC industry to manage and exchange information among various stakeholders such as owners, designers, contractors, and construction managers. The development of BIM provides a chance for construction managers to accomplish some of their work by computer. In particular, BIM can digitally provide the geometric characteristics of every components of the building (Marzouk & Aty, 2012). BIM, therefore, has the potential to realize automatic construction because of its information-rich and object-based model. BIM has the capability for 3D visualizations of project design, or for convenient cost estimating tool because of its built-in features. BIM also benefits the creation of the construction sequence, material ordering, fabrication and delivery. Additionally, conflict, interference and clash can be detected in BIM model at early stage (Azhar, 2011).

Revit, one of the most popular BIM software application, can be used to develop a complete model for the home including all framing, windows and doors. This provides a starting point for development of a robotic model for house construction. Revit uses a NET framework application-programming interface (API), which enables users to develop plug-ins to realize customize requirements (Irizarry, Karan, & Jalaei, 2013). With Revit API, additional functions can be achieved for supply chain tracking, automatic scheduling and etc.

IFC and GUID

Industry foundation classes (IFC) is a type of BIM specification that is adopted in the research into and development of computer applications for building, construction and facility management. It also focuses on the process of modelling and aims to present building information more efficiently (Fu et al., 2006). Building components details can be obtained from an IFC file describing the objects' structure and physical elements (Fu et al., 2006). IFC has two sets of XML schema variants, STEP and ifcXML. Extensible Markup Language (XML) files store and transfer BIM information metadata in software programs such as Revit (Panushev, 2011).

Panushev (2011) show how to define building components further, a globally unique identifier (GUID) is used in Revit to give each component a unique ID. This targets the exact and unique component in the integrated 3D model. This method is quick and convenient because GUID are unique for each logical object. GUID is a standard way of identifying the models and will provide a platform for the collaboration and communication among general contractor, sub-contractor, fabricator, etc. in the future development of construction related goods and materials.

BIM Based Technology

Konig, Koch, Habenicht, and Spieckermann (2012) show that the development of BIM enables many construction technologies to become possible and more importantly to be widely dispersed into the market. In order to support construction scheduling and estimating, BIM can provide intuitive 3D models and easy quantity takeoff ability. Sulankivi, Makela, and Kiviniemi (2009) stated that the 2D drawing cannot meet the demand of planning the site logistic and layout any more. With the use of 4D BIM models in the future, site layout can be more complex and dynamic. Heesom and Mahdjoubi (2004) illustrated that when the schedule and sequence are combined with the 3D BIM models, 4D construction visualization technique can help the construction management team to better control a job because it enables project managers to predict the issues that may cause cost overruns and delay. Tulke, Nour, and Beucke (2008) developed an algorithm for boundary representation of BIM to support the creation of construction schedule. Konig et al. (2012) presented a concept showing that creating templates that can generate the construction process and method for future use. This technology is based on the context of BIM, although the logical extension is to AI systems (Abelson, Sussman, & Sussman, 1987).

They developed an approach to generate input data for construction simulation by combining BIM data and reusable templates. Kim, Anderson, Lee, and Hildreth (2013) established a framework for using the data that extracted from BIM model to automatically generate construction schedule. They proposed a work flow of generating construction schedule based on RS Means Daily Productivity and sequencing rules by building element data from BIM model.

BIM also has its advantage in the aspect of prefabrication and construction site operations (Vähä, Heikkilä, Kilpeläinen, Järviluoma, & Gambao, 2013). With the product information obtained from the BIM model based on IFC (Industry Foundation Classes) standard, an overall plan for a producer has been created to illustrate the advantage that BIM has in prefabrication (Babič, Podbreznik, & Rebolj, 2010).

Nawari (2012) states that BIM can help improve prefabrication productivity, element quality and provide a better construction working environment especially when projects is complex such as K-12 school, industrial and hospital projects

In the aspect of construction site operation and supply chain management, BIM also has its advantages. BIM enables project manager to check the quality of a construction project by comparing the visualized model and real-time object (Hwang & Liu, 2010). Irizarry et al. (2013) presented a method that using BIM and GIS (Geographic information system) to monitor and track the supply chain of the materials need for construction projects.

PDCA Cycle

In order to develop an idea of automatic construction management, certain management processes have to be followed by the management team. The famous quality manager Deming developed the PDCA concept. Deming's plan-do-check-action (PDCA) was originally designed for quality control (Deming, 2000).

Since his early work in the 1950's significant research has shown conclusively that the PDCA cycle is a positive way to control a repetitive project and can not only reduce cost and waste, but also greatly increase project quality. Integrated with the PDCA cycle, also called a Deming cycle, automatic building scheduling and construction may become realistic (Deming, 2000).

Meiling, Sandberg, and Johnsson (2014) use PDCA method in construction industries, showing that PDCA method can reduce deviation and increase project quality. The Deming cycle is based on speeding up repetitive work but the human often perceives the building construction work as non-repetitive. The perception is that construction projects have the nature of uniqueness. However, a number of modern builders have moved to partial adoption of the Deming cycle, including AV Jennings in Australia.

Pseudocode

Pseudo-code is a type of code that can be used to develop computer programs using an abstract language remote from a real language such as Lisp, (Winston & Horn, 1989)formatted with a high level of information.

Zobel (2004) shows that while it is based on the computer-based languages, it is mostly used for human reading instead of machine reading. This type of code can be viewed as the third level code in the movement from first level machine code to computer programming languages such as Lisp and Fortran, which represent the second level, to natural language code used as descriptive tool (Metcalf, Reid, & Cohen, 2008; NK., 1997; Winston & Horn, 1989). Figure 1 shows a pseudo-code example compared directly to the code (Watts, 2004).

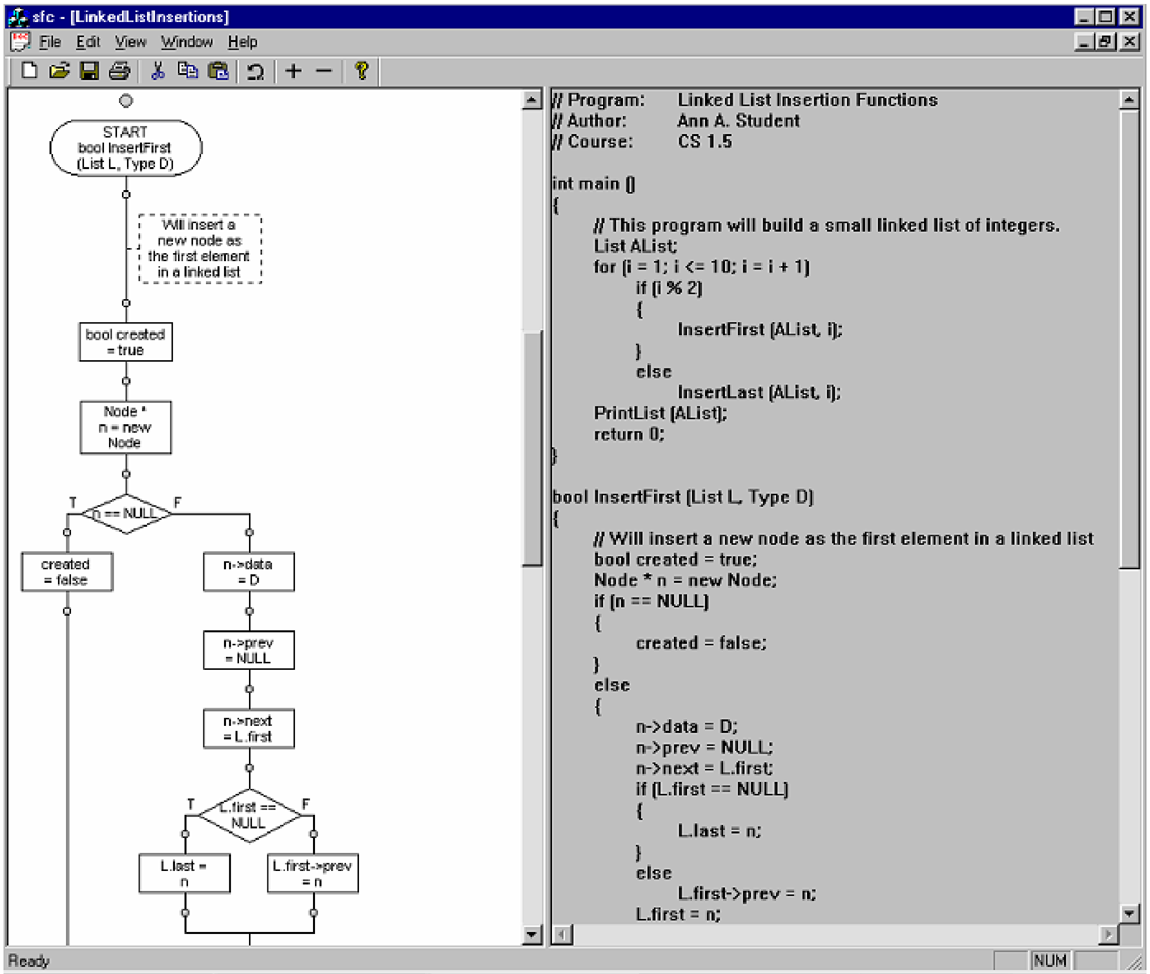

Figure 1. Example of Flow Chart and Pseudo-Code from Watts (2004)

Construction Positioning and Tracking

Luhtala, Kilpinen, and Anttila (1994) in discussing aspects of supply chain management for the construction industry, highlight the existence of problems such as the unknown or changing requirements of the customer, the change of schedule of the customer, and the synchronizing of the arrival of the components. These types of problems are easy to solve in traditional make-to-order supply chains, such as feeds the goods into a Walmart, but less so for a one off job.

Construction positioning on the job site and the tracking of the material supply chain is a critical task, and many techniques have been studies such as RFID, GPS, laser and photometry.

Radio Frequency Identification (RFID) uses radio frequencies to capture and transmit data in the field. Jaselskis, Anderson, Jahren, Rodriguez, and Njos (1995) show that in 1995, a study about utilizing RFID technique in construction industry was conducted and stated that RFID can be used in construction supply chain and project management.

For example, the RFID tags on the concrete trucks contain information such as the time of the type of the concrete, the time and date of loading, mixing and delivery He, Tan, Lee, and Li (2009) discussed how RFID and GPS can be integrated when tracking the supply chain and the benefits of applying RFID technique in supply chain control in construction. RFID technology can also be applied to help construction management because of the passive data and its ability to provide communication between construction processes using computer program (Chae, Yun, Han, & Kwon, 2010). Wang, Lin, and Lin (2007) show that RFID can be used as part of a tracking and information sharing system to monitor the construction supply chain and building progress. Research also shows that two types of automated processes are available to develop the RFID-based tracking process. One is semi-automated (SA) process which means the RFID tags can be attached to the component individually and scanned by human workers. Fully-automated (FA) process is that the readers are installed at the forklifts or entries so that human effort are minimized or nearly eliminated (Demiralp, Guven, & Ergen, 2012).

The RFID technique can also help identify the position of people and material in the construction field, which in turn enables the computer to monitor the job site condition (Ko, 2013). There are of course interesting ethical issues in this use of technology that will slowly be resolved, but ultimately one can perceive the day when all humans will be tracked.

Shoarinejad, Soltan, and Moshfeghi (2012) stated that an RFID location system can be created to the RFID tag that is then associated with GPS information for the RFID reader. Location information can be obtained accurately. Also a center locating system is designed to track the real-time location for the RFID (Luo, Xu, & Xu, 2010).

Song, Haas, and Caldas (2006). Song et al.'s research presents a proximity localization system using a rover where 10 to 20 RFID tags are installed on the construction site so that the location of the RFID readers can be calculated with the help of GPS receiver on the rover.

A study of using UAVs to construct a 6-m-tall tower automatically is presented in 2012 (Gramazio, Kohler, & D'Andrea, 2012). It uses the motion capture system to track the location and position of objects in the space. The system is based on wired and wireless communications. In order to increase the accuracy of the placement of elements, the position of the drone is constantly monitored. The element will not be placed if the detected error is too large. The result is that 91.2% of the placements are within the maximum of 25mm error.

The problem of tracking and positioning technique rests on the accuracy of any machine required to place building elements. Table 1 shows the accuracy and budget for three categories of GPS receivers when assembling components (Wing, Eklund, & Kellogg, 2005):

Table 1

GPS Receivers' Categories

Name	Accuracy	Budget
Survey-grade GPS	1 cm	$25,000
Mapping-grade GPS	2-5 m	$2,000 - $12,000
Consumer-grade GPS	15-20 m	<= $100

Pradhananga and Teizer (2013) demonstrate how GPS, GIS and other location technology are used for the purpose of positioning in construction type uses. A Real Time Kinematic (RTK) GPS is designed to control and measure the vertical position and surface profiling for equipment and materials. Global positioning system are used to determine the true position of the elements. All of the data is stored as GPS data, GIS models using a WAN (Wide Area Network) to serve as a centralized monitoring systems. All of this was not possible a decade ago.

Wing et al. (2005) show that laser techniques have been used in the construction industry for both object monitoring and quality controls. This system can achieve a higher accuracy level than GPS devices at a centimeter of accuracy in the real world.

Makynen, Kostamovaara, and Myllyla (1994) show that laser techniques have been used to track a large sample object to an accuracy of ± 0.3 mm. An experiment completed by Bosché using laser scanning compares the quality of as-built buildings and as-designed models. This system ultimately presented a new way of building dimension calculation (Bosché, 2010).

Studies show that visual data analysis in the development phase of construction has been utilized for a long time (Winston & Horn, 1989). Later in this field, in 2000, Stamos and Allen developed a method of creating 3D models with 2D images (Stamos & Allen, 2000). Bohn and Teizer, for example, describe a method using camera and photographs to monitor a construction project (Bohn & Teizer, 2009). They use hi-resolution construction cameras to observe construction activities, including people, instrument and materials. This technology provides a method to generate the data of the existing construction site conditions, which benefits quality management and building process monitoring. Nichols (1989) demonstrated an AI system could be developed in AutoCAD using AutoLISP, and used a Fortran program to design sewers, complete the drafting and quantity takeoff.

Robot Construction Technology

In 1974, a study showed a computer program could generate construction plan for robots to build simple building structure, such as blocks. The case study used in this research shows different plans for forming several blocks into different shapes in logistic sequence (Fahlman, 1974). Stroupe et al. demonstrated a multi-robot construction to perform construction assembly jobs in natural terrain. The experimental robot can function acquisition, operating, transporting and placing object precisely (Stroupe, Huntsberger, Okon, Aghazarian, & Robinson, 2005). Various types of construction robots are designed for specific construction works. For example, Choi et al. presents a design for a construction robot that uses pneumatic actuator to help construction workers on placing panels or tile. The robot they designed had an accuracy of ± 3 mm position resolution (Choi, Han, Lee, & Lee, 2005). Another study demonstrates a design for a 3-DOF manipulator robot used for curtain wall installation (Yu, Lee, Han, Lee, & Lee, 2007). Chu et al. (2013) studied robot-based steel construction technology to show that human labor can be replaced by robots in the near future.

Summary

Robotic construction is coming, it is only a matter of time and effort. The economic returns are too high not to make this transition.

CHAPTER III

METHODOLOGY

Introduction

This chapter outlines the methodology to design a computer controlled automatic construction work flow, describes how information technology, management technology and robot technology should work together and shows how an information system is designed to integrate the supply chain and field construction activity.

The assumed period of construction described in this thesis is from the design of BIM model to the completion of the building structure. The research purpose is to illustrate the techniques to be developed and not to develop the techniques that is future research beyond this scope of work.

Information System

An integrated information system consists of two major parts that must control construction design and control the construction work.

In the construction design stage, three phases are required to complete the construction plans including design and supplier selection, supplier feedback and construction plan generation. A simple model from civil construction work for a drainage project is used to illustrate the methods used for the study. The first step is to determine the scope of the work, in this sample case, a drainage system for a residential subdivision at Maryland, Newcastle, NSW in Australia.

Figure 2 shows a typical residential suburb in New South Wales Australia developed in the period from 1980 till 1995. The drainage system at this location was designed using a FORTRAN program that could handle calculation of the flows and provide a pipe design, detailed plans and quantity calculations.

Figure 2. Maryland NSW - Drainage System, from Google Earth (2016)

In this case, determination of the design standards is required for the work. The design is to the Land Commission of NSW Design Standards. The material selection must occur, which is rubber ring jointed drainage pipe as shown in Figure 3.

Figure 4 shows the stretch of Maryland Drive which is the main road shown in Figure 2. The type of drainage pit used in the system is shown on the left hand side of the road and the roadway forms the overland flow path for the storms with a recurrence interval in excess of 10 years.

Figure 3. Rubber Ring Jointed Drainage Pipe

Figure 4. Maryland Drive – Drainage System, from Google Earth (2016)

Figure 5 shows the raw drainage line designs for two of the end pipes in the system, the level of information available to the construction manager can be seen on the drawing.

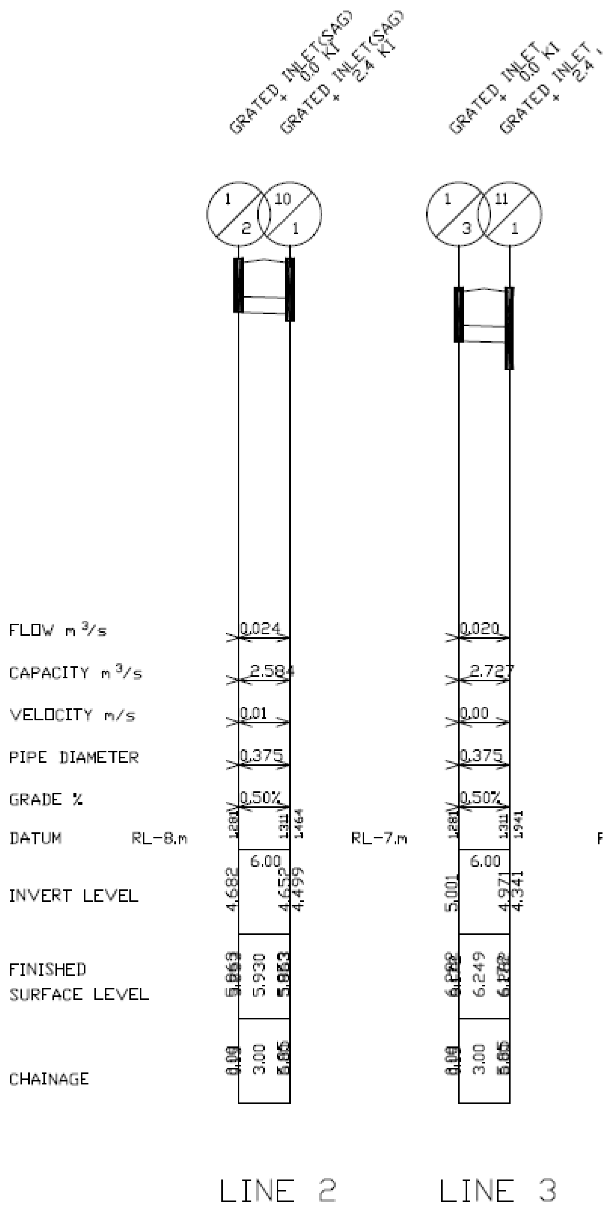

Figure 5. Drainage Line Designs

Figure 5 plans with the layout provide a competent contractor with all of the required information to build the drainage system.

While construction controlling process includes supply chain tracking and on-site component assembling and tracking. The entire process shares the BIM data and other customize information that enables involved parties to communicate with each other in order to automatize construction activities.

Preconstruction System

The preconstruction system generates a construction controlling plan for a specific construction process determined by the design requirements and the potential suppliers. This plan provides the information to control the location, placement and method of construction of all elements.

The process is based on the BIM model that has been created by designers at an object level of detail. Figure 5 shows a very simple model, but in this case, one can determine:

- The types of all pipes
- Lengths of pipes required
- Types of pits requires
- Pit location and lintel length
- Grades and elevations on the pipes and pits

Information including element dimensions, material, position and ID is specifically defined for each component. The definition of a building component is what will be installed individually on the construction site.

A site logistic plan specifying the site area, entry location, material storage area and equipment standby area should also be available in the system database. The site logistic plan defines the project base point so that a site coordinate system can be generated. The work shown on Figure 5 is based on the state co-ordinate system.

By creating the site coordinate system, every item including point, area and space can be presented and recorded in coordinates. The logistic plan can be either defined by designers or generated automatically by the system program. Once all the information is available, an on-site construction schedule is generated based on the framework provided by Kim et al. (2013) based on data extracted from BIM model.

Figure 6 shows the process of the preconstruction automatic system. After confirming all the information required for the project, the system will select potential suppliers for each building component and send the BIM model containing the data that the suppliers need to manufacture the construction component. In the example provided in Figure 5, a pipe supplier could be asked to provide a quote for 600 meters of 375 mm drainage pipe, delivered to the site.

As the potential suppliers receive the data, this functions as an invitation for bids (IFB) including the BIM model and the schedule of the specific item required to be appear on the job site, the program on the suppliers' side is able to decide if they can accept the bid. The pipe supplier program may respond, delivery on the 10th instant and a price and the bid can then be reviewed against the job criteria.

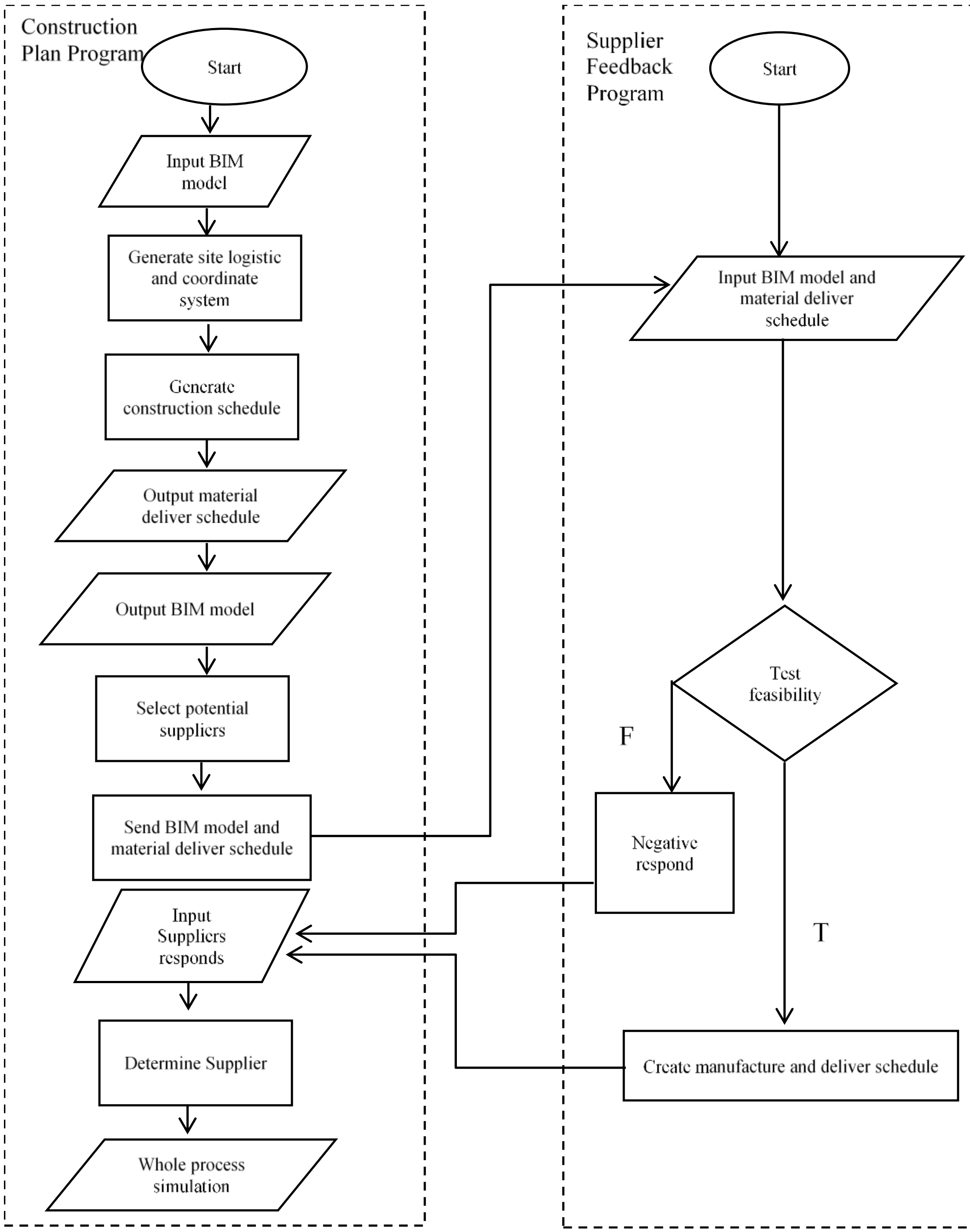

Figure 6. Flowchart of Preconstruction Process

The manufacturers schedule including manufacture time, shipping time, and deliver time will be created if the bid is accepted.

Data such as the elements' physical dimension and materials also should be saved as ifcXML format. The supplier's reference data provides the purchaser with the information on the final product. With the help of IFC a platform is provided for the information sharing between owners and suppliers. IFC can be extracted from BIM software such as Revit. The supplier's system made the decision by checking the productivity of its manufacture efficiency, raw material inventory and existing working or delivering schedule. The data flow of this process is shown in Figure 7.

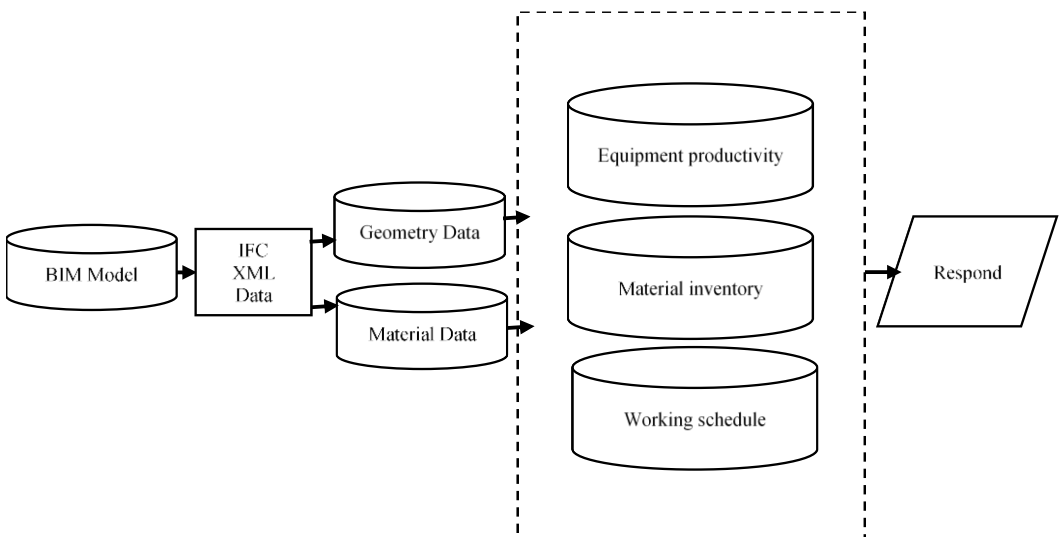

Figure 7. Data Flow in Supplier Responding

The supplier system then makes response to central system and the purchasers system will decide which suppliers to be selected and make positive response.

The selection of the suppliers is based often on multiple factors, such as the success rate of the suppliers to complete their task on their previous project, the distance between the suppliers' location and the job site (which is also a consideration for LEED), the quantity of components that the supplier is able to provide.

When this exchange of information is finished, a detailed automatic construction plan showing the whole simulated process will be generated and saved for the construction controlling stage. The plan includes the tracking of each construction component based on their manufacture process, location and position. The time points such as the component is manufactured, prepared for shipment, delivered to the material storage area on the job site are planned and saved to the database. The GPS location and the route for the vehicle used to transport the component is estimated by the suppliers' system using GIS information. Also, in order to realize the robot construction for each component, the coordinate data for each component is included in the automatic construction plan as defined in the design phase.

Construction Control System

A construction control system is designed to control and monitor the shipping and installation process. It is another part of the integrated information system, which aims to operate the process and check the real-time status of the progress. If accidents or errors occur in any period of the process, error correction will be made to ensure the process running successfully. When the manufacture begins, the suppliers will activate the process according to their schedule. At the meantime, tags are attached to the component to the points that have been predefined in the schedule. RFID readers are installed onto each place that indicates the change of status for RFID tags. Also, a transportation route is determined so that location can be monitored during transportation. After the product is transported to the job site and deposited in the storage area, the program will know the availability and can as required instruct the robots to commence the installation work.

Song et al. (2006) observes that tracking materials on construction projects requires two different levels of position accuracy. One of which is the tracking of supply chain of construction materials via using Global Positioning System (GPS) and RFID. The second is using GPS and RFID to locate the construction object to rough position and then using laser to locate the final position and place the object. The tracking and positioning technology used in the system is shown in Figure 8.

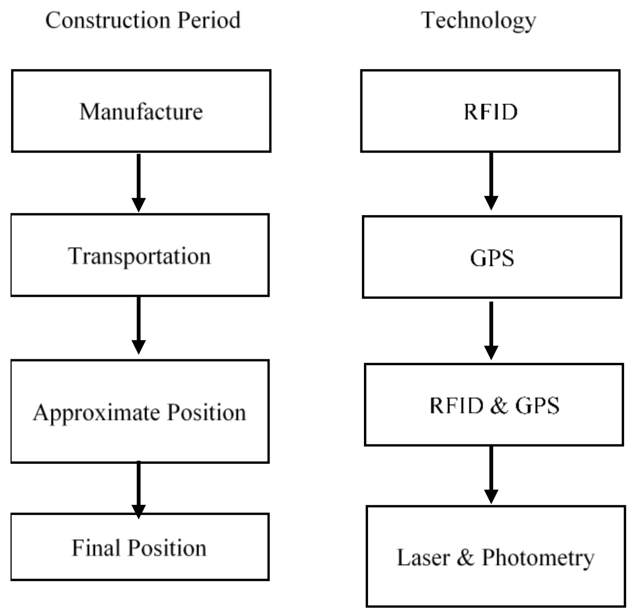

Figure 8. Technology Used in Different Construction Controlling Periods

The control system flowchart is shown in Figure 9.

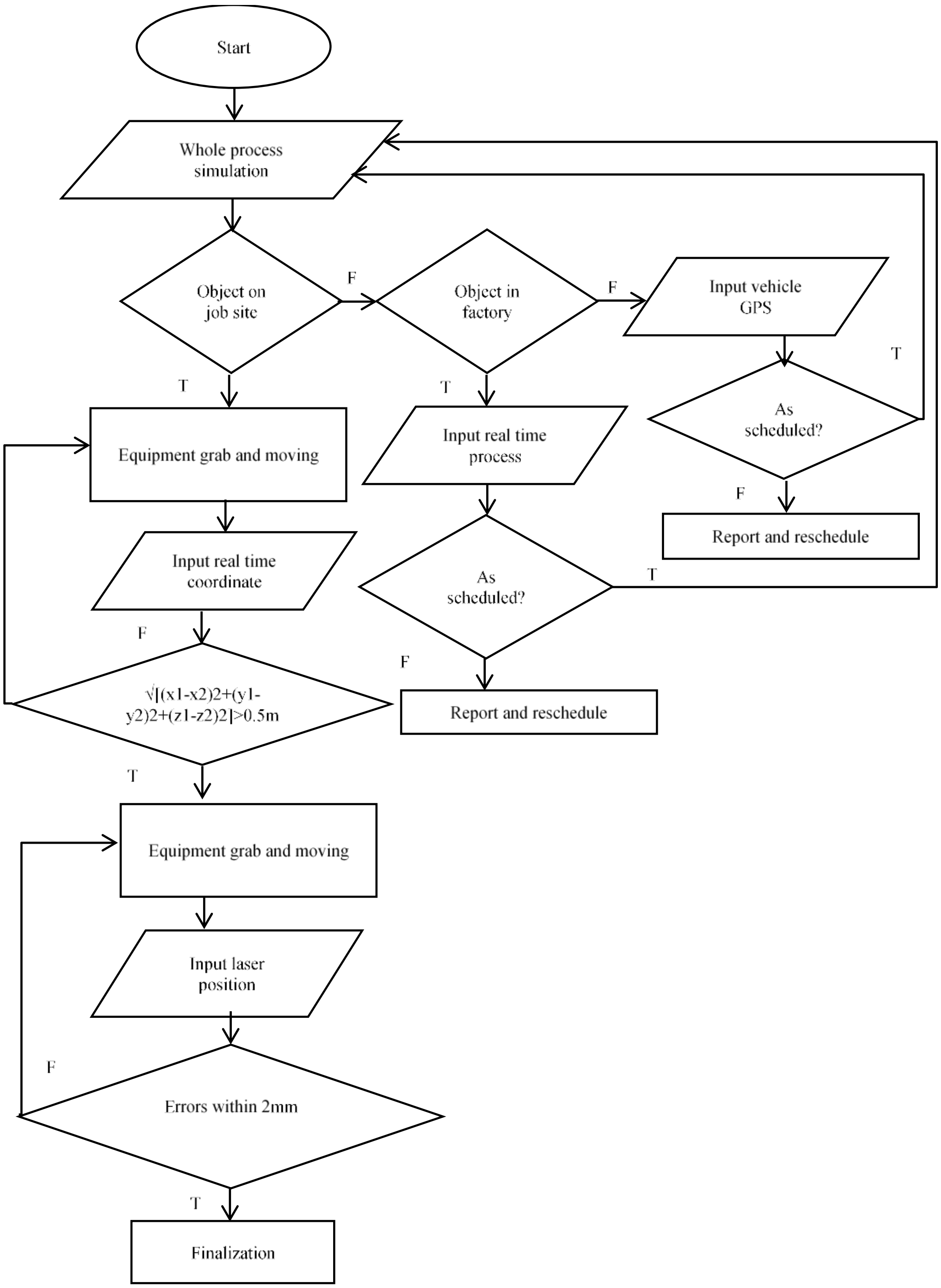

Figure 9. Flow Chart of Construction Controlling System

Accuracy in the supply chain occurs with:

1. each element of the building or project is well defined
2. each element is recorded in the system and is GUID tagged separately
3. each GUID represents the smallest unit in the building models
4. for RFID and GPS tracking, RFID readers are installed on the entry of each factory, warehouse, vehicles and wherever change of location occurs
5. GPS tracker is installed on each vehicle
6. data is to be available both in real time and recoded into the system
7. delivery and placement time and date is coded to the RFID tag (element)
8. Required (designed) date, time, location and GPS check point for each vehicle
9. Real-time GPS information of the vehicle
10. Central and continuous monitoring of all elements of the chain

The second level of computer control system is to instruct the robots to place the element (or prefabricated object) into its spatial location. This requires a high accuracy than the GPS can provide.

Laser technique improves the level of precision. For example, Nikon iSpace or GPS laser based indoor GPS system can offer a 3D positioning system at an accuracy of ± 200µm.

The positioning process mainly consists of two parts: approximate positioning and exact positioning. The approximate positioning enables RFID and GPS to place the element to a location within about 0.5 m while the exact positioning process calibrate the spatial position of the object and finalize the object in an error of 2 mm comparing to the BIM model.

An element has six degrees of freedom (DOF) to define its position in real world. Three of the DOFs are the transportation of the element, containing moving up and down, left and right and forward and backward. Other three DOFs are to describe the self-rotation, which are pitching, yawing and rolling. In order to instruct the robot or automated equipment to place the element, 6 DOFs should be pre-defined for each construction element. DOF data is saved in the database. The insertion point and angle set is defined for each element in the BIM model.

The RFID reader system is created to form a spatial coordinate system which can detect and calculate the coordinate of the insertion points (RFID tag). And the robot or machine can follow the instruction of designed computer program and place the item. Once an object is placed, techniques such as laser can be used to compare the object position with the BIM model in order to check and as required to reposition the objects.

Figure 10 shows the tracking system.

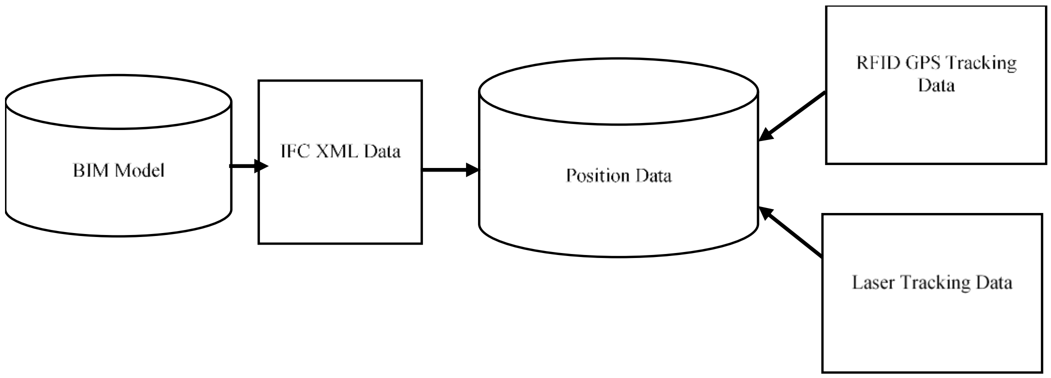

Figure 10. Data Flow in Component Tracking

Pseudocode Design

The program algorithm follows the procedures outlined in the PDCA management cycle. In order to present the process pseudo-code is created which consists of four phases:

- Automatic construction plan program pseudo-code
- Supplier feedback program pseudo-code
- Construction plan generation program pseudo-code
- Construction controlling program pseudo-code

Figure 11 shows the Automatic construction plan program.

```
Automatic construction plan program
        //Input BIM model THEN
               //If  3D  building  model  envelop  is  defined,  components
completed THEN
               //Define project scope #. Give ID to each element
                       //Generate site logistic plan
                             //Define  base  point;  base  point  coordinate
(x,y,z) = (0,0,0);
                             //Print functional areas coordinates
                       //Generate element positioning data
                             //Define element tracking point;
                             //Print element DOFs # 6DOFs includes spatial
coordinates (x,y,z) and rotation (xr,yr,zr)#
                       //Generate on-site construction schedule # Based on
element quantity information and material composition# THEN
                             //Input project GPS NMEA
                                     //Find suppliers within 50 miles
                                     //If suppliers number = 0
                                               //Find  suppliers  within  100
miles THEN
                                               //Else
                                               //Send  BIM  model;  element
DOF, on-site construction schedule
         //Else
         //modify BIM model0
         //End if
```

Figure 11. Automatic Construction Program Pseudocode Phase 1

Figure 12 shows the supplier feedback program.

```
Supplier feedback program
//Input BIM model; element DOF; on-site construction schedule
//Extract element material data; quantity data
     //Check inventory
            //IF material available THEN
                    //Extract element schedule
                    //Check existing schedule
                           //IF no conflict THEN
                               //Generate schedule
                               //RETURN schedule
                           //ELSE
                           //RETURN false
                    //ELSE
                    //RETURN false
            //END IF
```

Figure 12. Automatic Construction Program Pseudocode Phase 2

Figure 13 shows the Automatic construction program.

```
Automatic construction plan program
        //Input Supplier feedback
               //IF supplier feedback data meet requirement
                      //Compare suppliers
                      //Select supplier
                      //Generate construction plan for process control
               //ELSE send BIM model; element DOF, on-site construction
schedule
        //END IF
```

Figure 13. Automatic Construction Program Pseudocode Phase 3

Figure 14 shows the Automatic construction program.

```
Control process
START
//INPUT construction plan
          //IF time = manufacture time
                 //call manufacture
                 //IF manufacture check point <= plan time +- tolerance
interval
                 //RETURN true
          //ELSE
                 //Reschedule time; record responsibility
          //IF time = shipping time
                    //call shipment
                    //check point <= deliver
                        //IF shipping check point <= plan time +- tolerance
interval
                        //RETURN true
          //ELSE
                //Reschedule time; record responsibility
          //IF time = deliver time
                   //check point <= deliver
                        //IF shipping check point <= plan time +- tolerance
interval
                        //RETURN true
         //IF time = install time
                //Call move robot
                        //IF coordinate √[(x1-x2)^2+(y1-y2)^2+(z1-
z2)^2]>0.5m
                               //Call robot calibrate position
                       //ELSE laser tracking
                               //IF error <= 2mm
                               //RETURN true
                               //ELSE Call robot calibrate position
                               //END IF
                       //END IF
         //END IF
```

Figure 14. Automatic Construction Program Pseudocode Phase 4

Case Study Design

In this research, a case study of a six-room wooden house project is used to present the idea of automatic construction system and to look at the use of Revit to provide the information for the automatic construction system. Only part of the building's components will be used in order to simplify the process. And another case study is presented to illustrate an on-site spatial positioning method. The following steps are taken for the case study of a six-room wooden house:

1. Preparation of the BIM model in Revit. Components listed as elements are constructed as a separate structure such as a column, a beam or a floor. And each component has a unique ID.
2. Generate a project coordinate system and site logistic plan
3. Determine the information needed to be defined in BIM model:
    - Geometric information
    - Material information
    - Component individual tracking point
    - Spatial information (6 DOFs)
4. Provide methods to determine the suppliers for each element
5. Prospective construction plan describing every step of construction process (supply chain process and site installation)
6. Methods to accurately position the building components

CHAPTER IV

CASE STUDY

Introduction

The case study presents the process of the computer controlled automatic construction system to verify the feasibility of applying this system for a real project. The case study consists of following sections:

- Information about the six-room wooden house
- Design and preconstruction process
- Suppliers feedback and generation of final construction plan
- Construction control and object positioning

Information About the Six-Room Wooden House

The building used in the case study is a six-room wooden house designed in 1921. A block located in Highland Park, on 3621 Cornell Ave, Dallas is used to illustrate the process. It is a simple colonial style house built in wood structure, concrete foundation and recast in stone or masonry (Building Plan Holding Corporation, 1921). The view of this particular six-room wooden house is shown in Figure 15 and its floor plan is shown in Figure 16.

Figure 15. View of the Six-Room Wooden House

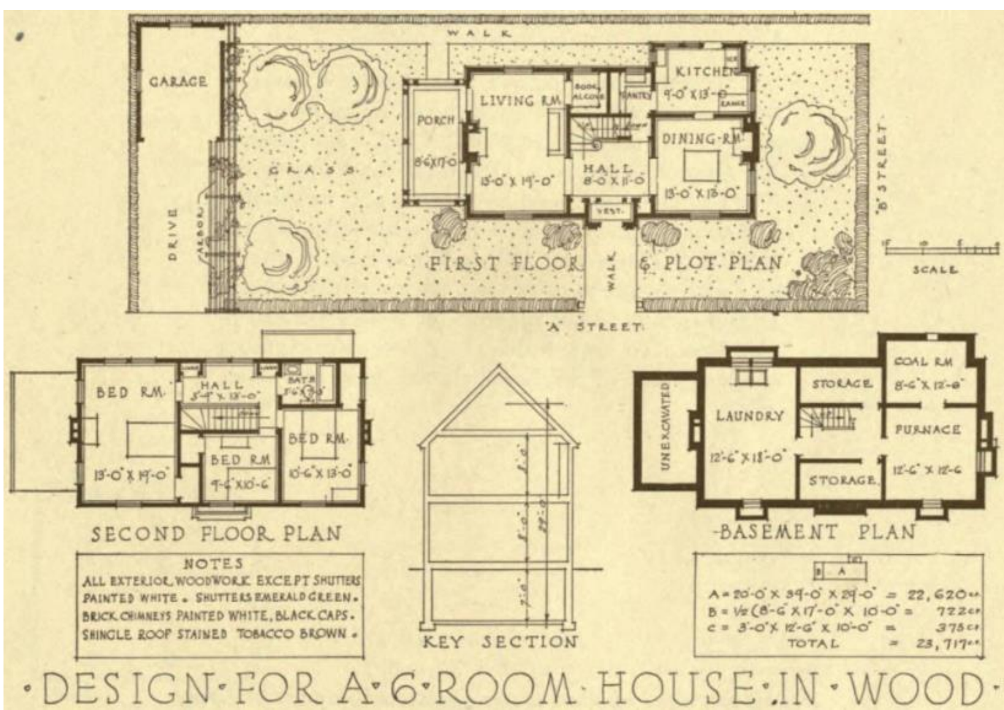

Figure 16. Floor Plan for Six-Room Wooden House

Design and Preconstruction Process

Wood (2015) created a BIM 3D model in REVIT 2016 for the Dises House for another research project. Permission was granted to use the work for this research.

Figure 17 shows the model developed by Wood.

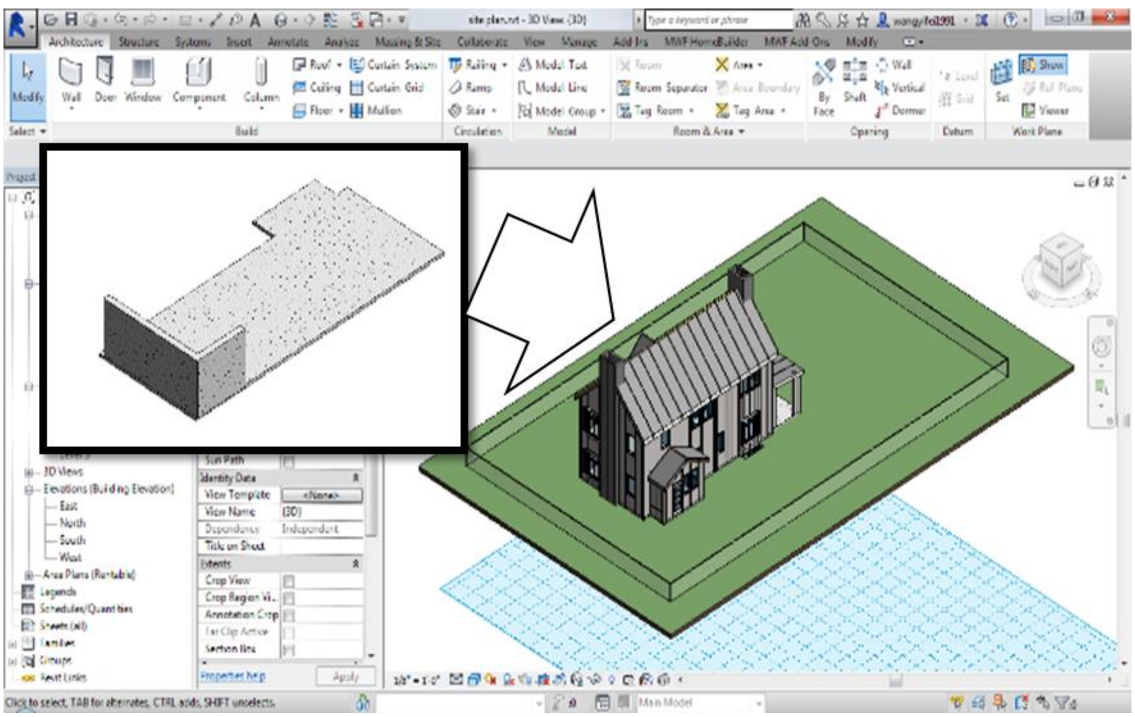

Figure 17. 3D Model of the Six-Room Wooden House in Revit 2016

Figure 18 shows the house in the 3D model. The basic building components are derived from this model. The next step is to develop a site logistics plan. The site logistic plan is designed to describe the location of the project base point and the designated areas such as material storage area, entrance and place for the equipment. Those areas can be presented by the relative coordinates and saved into the database for future use of generating the computer controlling plans.

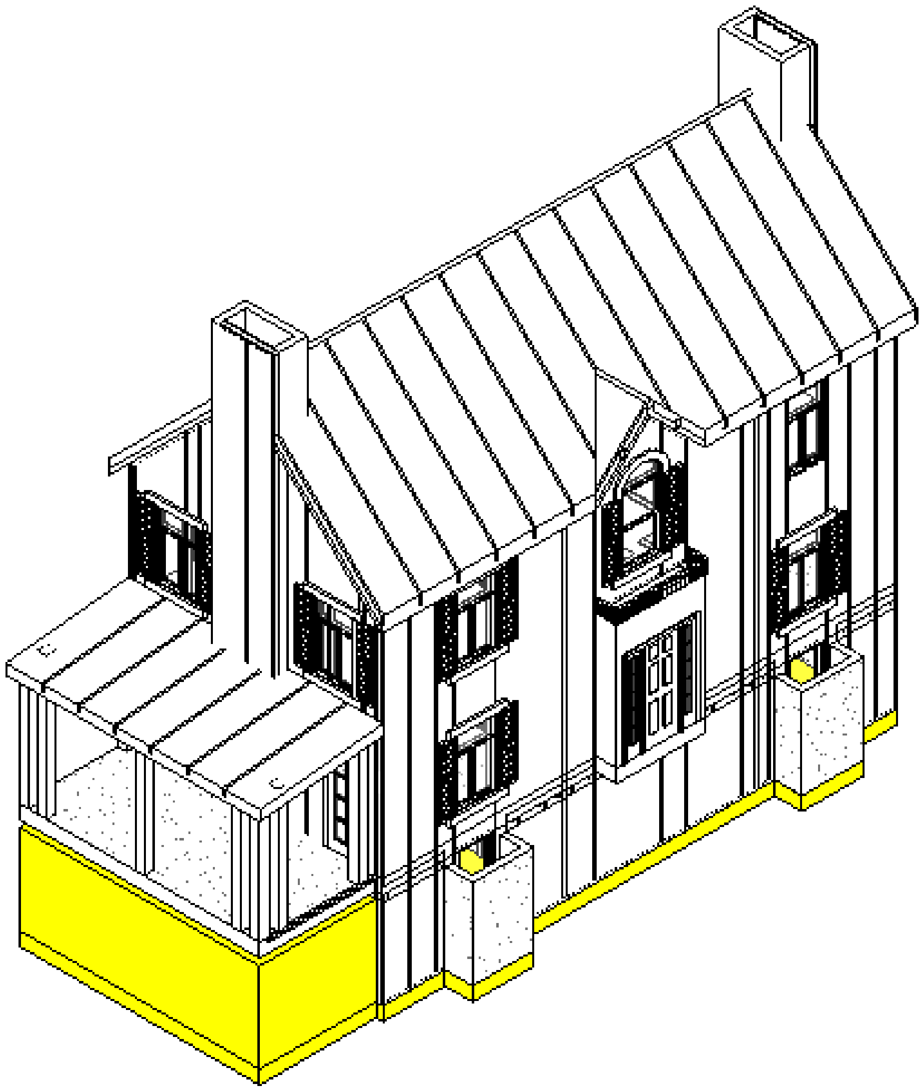

Figure 18. Sample Building Components Used in the Case Study

Only regular polygon and cylinder are presented in this case study. A 2D area or a line is represented by the endpoints of the shape and its relative elevation to the project base point. 3D space is represented by the 2D area endpoints and the upper and lower elevation. Figure 19 shows the site logistics plan and the projects defined base point and projections.

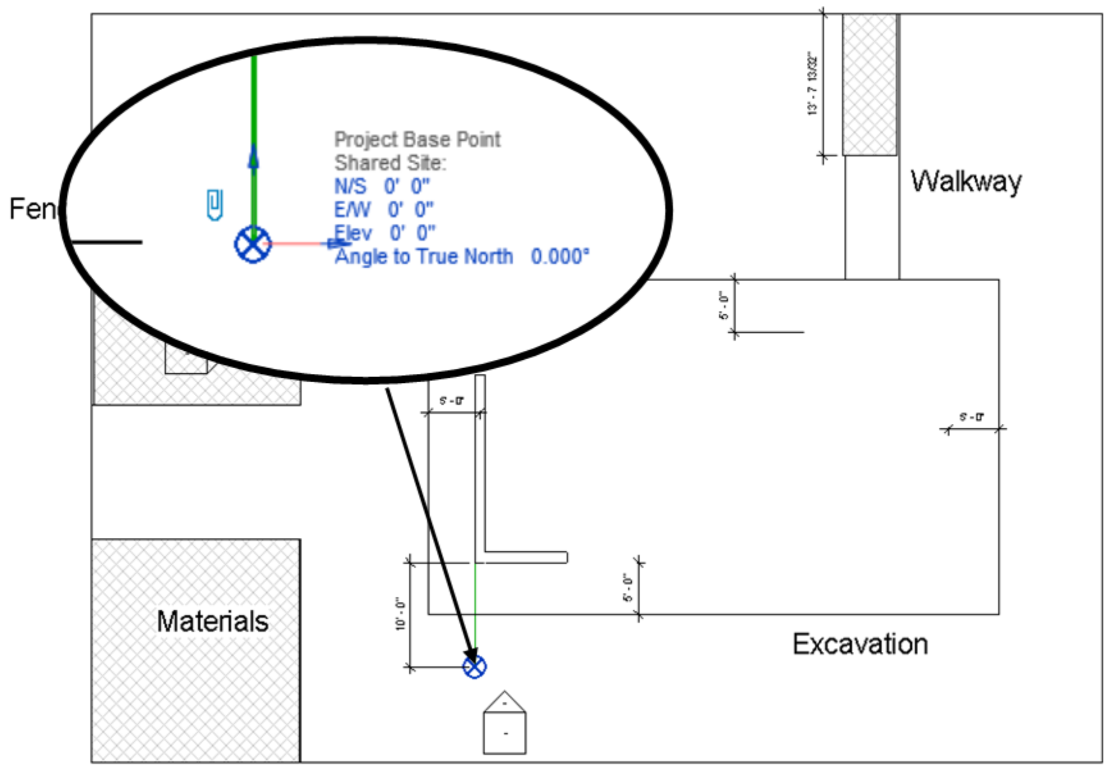

Figure 19. Site Logistic and Project Base Point

Table 2 shows an example of the site coordinate system.

Table 2

Example of Site Layout Coordinate Data

Area	Shape	Coordinate (N/S, E/W, Elevation)
Entrance	Line	(36' 1 105/128", 62' 7", 0)
		(41' 5 23/64", 62' 7", 0)
		(0)
Foundation trench	Cuboid	(-4' 6", 37' 1", 0)
		(51' 3", 37' 1", 0)
		(-4' 6", 5' 0", 0)
		(51' 3", 5' 0", 0)
		(8’ 6’’)
		(0)
Material	Rectangular	(-37' 3 41/64", 12' 3", 0)
		(-16' 11 3/4", 12' 3", 0)
		(-16' 11 3/4", -9' 1 53/64", 0)
		(-37' 3 41/64", -9' 1 53/64", 0)
		(0)
Equipment	Rectangular	(-37' 6", 50' 1 19/128", 0)
		(-17' 3 41/64", 50' 1 19/128", 0)
		(-17' 3 41/64", 25' 1 19/128", 0)
		(-37' 6", 25' 1 19/128", 0) (0)

A construction sequence is created by an automatic generation of construction sequence technique that produces construction schedule from the data provided by BIM data. Table 3 shows the schedule that applied to the case study. After these two process is completed, the program will select the suppliers that can provide the construction components according to the geo-location information, historical data and customized data of potential suppliers. Then the program is able to send the BIM model and schedule related to each element to the potential suppliers.

Table 3

Example of Construction Schedule Data

Task Name	Duration	Predecessors	Construction Start Time	End Time
Excavation	2 Days		8:00 2/15/16	17:00 2/16/16
Foundation Slab	2 Hours	Excavation	8:00 2/17/16	10:00 2/17/16
Foundation Wall 1	2 Hours	Foundation Slab	10:00 2/17/16	12:00 2/17/16
Foundation Wall 2	2 Hours	Foundation Slab	10:00 2/17/16	12:00 2/17/16

Table 4 shows an example of building element information.

Table 4

Example of Building Element Information

ID	Name	IFC-GUID	Material
387665	Structural Foundations: Foundation Slab: 6" Foundation Slab	e9ac07c9-f327-4411-80a3-5b8c42d57494	Concrete - Precast Concrete
310304	Walls: Basic Wall: Foundation - 12" Concrete	7f68d8a2-3380-4253-98da-a454d25b376b	Concrete - Precast Concrete
310084	Walls: Basic Wall: Foundation - 12" Concrete	7f68d8a2-3380-4253-98da-a454d25b300f	Concrete - Precast Concrete

In this case study, the proposed project is located in Highland Park, on 3621 Cornell Ave, Dallas. Potential suppliers are selected based on the distance to the project location. Figure 20 shows the project site and a 3 mile radius circle. Potential suppliers within 3 miles of the project are selected to request bid prices.

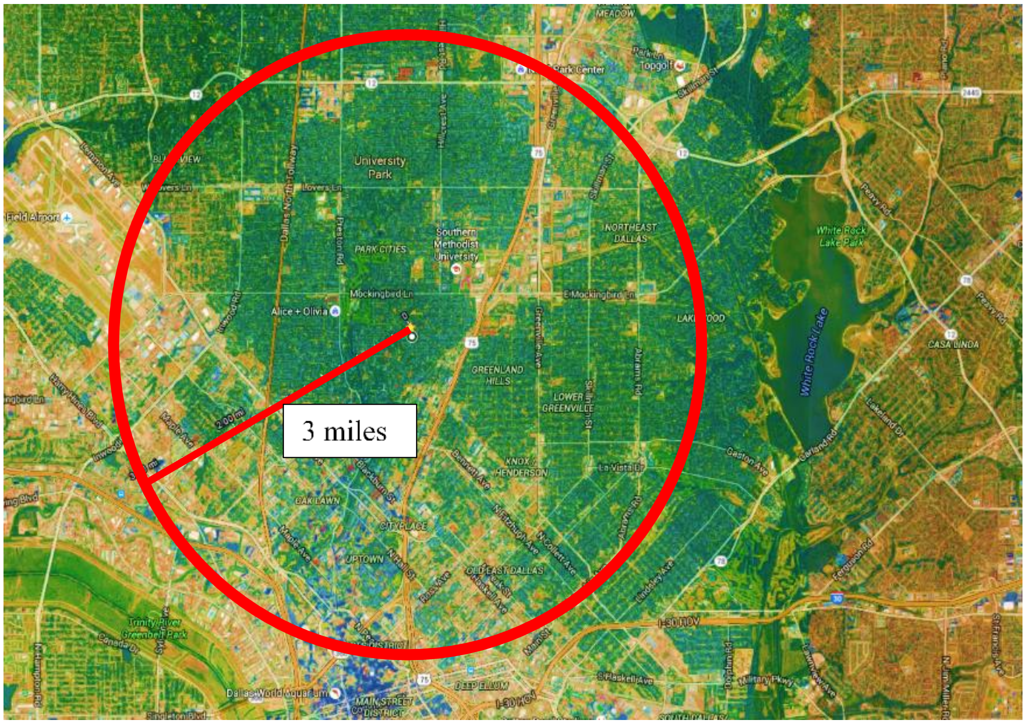

Figure 20. Project Location from Google Maps (2016)

The system sends the bidding package, Table 5, to those chosen suppliers and waits for their feedbacks.

Table 5

Suppliers Within 3miles After Google Maps (2016)

Name	Distance (mile)
Proficient Concrete	2.7
Vince Hagan Co.	1.64
Concrete Solution	2.77
Power Jack Foundation Repair	0.8

Suppliers Feedback and Generation of Final Construction Plan

The next progress is the suppliers' response to the system. The sub-program at the suppliers' side receives and checks the suppliers' ability and schedule to determine whether they are able to accept the project. If the manufacturer can accomplish the task, the schedule including the time of the completion of manufacture, shipping and transfer time to the vehicle and the deliver time will be created. This information data will be saved to the final construction control plan.

In this case study, the time calculation is based on the following algorithm. Different time points are calculated including construction time, delivery time, shipping time and manufacture time. The construction time defines the point that the robot begins to manipulate the object. And the deliver time means the time that the object will be delivered on the job site passing through the entrance of the job site. The time is estimated according to the scheduled construction start time minus the time needed for the object to be transferred to the storage area and the time to unload and placed to the storage area. The shipping time is calculated on the basis of the required shipping duration that has been obtained from GIS applications. Manufacture time and finish time is affected by shipping time and time required to prepare for the shipping. These time spots should be defined so that when the actual progress starts, sensors or readers will record these times and compare them to the construction plan in the design phase. The time estimated to transport each patch is shown in Figure 21 showing the most probable shipping time is 14min from the suppliers' location to the project site by automobiles.

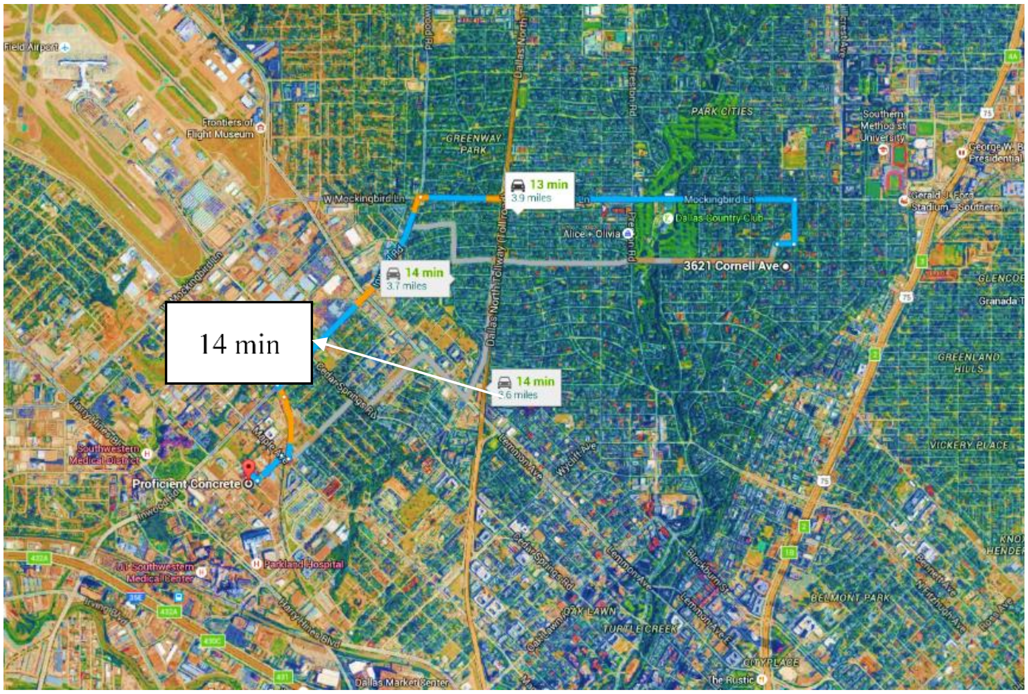

Figure 21. Duration for Transportation from Google Maps (2016)

After the server receives the response from all the suppliers, the program then selects the suppliers for specific category of object. In this case study, only the precast concrete suppliers are included. A typical schedule such as would be provided by Proficient Concrete showing the manufacture schedule for each building component is shown in Table 6 and Table 7.

Table 6

Data Included in Construction Controlling Plan (1)

ID	Name	Supplier	Shipping Duration	Manufacture Completion Time	Shipping Time
387665	Foundation Slab	Proficient Concrete	14 min	7:21 2/17/16	7:31 2/17/16
310304	Basic Wall: Foundation	Proficient Concrete	14 min	9:21 2/17/16	9:31 2/17/16
310084	Basic Wall: Foundation	Proficient Concrete	14 min	9:21 2/17/16	9:31 2/17/16

Table 7

Data Included in Construction Controlling Plan (2)

ID	Deliver Time	Pick-up Time	Installation Time	Spatial DOF	Self DOF
387665	7:50 2/17/16	7:50 2/17/16	8:00 2/17/16	(0' 0",10' 0", -8' 6")	(0,0,0)
310304	9:50 2/17/16	9:50 2/17/16	10:00 2/17/16	(0' 0",10' 0",0' 0")	(90° ,0,0)
310084	9:50 2/17/16	9:50 2/17/16	10:00 2/17/16	(0' 0",28' 0",0' 0")	(0, 90° ,0)

Figure 22 shows the location of the project control point in a 3D plot.

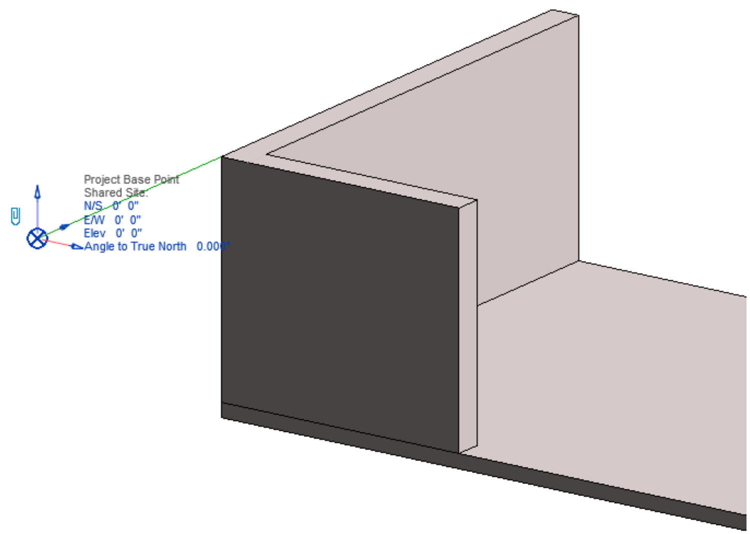

Figure 22. Project Coordinate System

Process Control

The next stage is the construction process. Suppliers attach RFID tags onto the objects. Tags are scanned so that the updated information of the building components can be saved to the server through the internet.

Time data will be read and checked when the object is on the terminal of the manufacture line, the entrance and exit of the factory, the gate of the vehicle, the entrance of the project site, or the storage area on the job site.

The onsite construction requires the action of object handling equipment such as construction robots. The idea is to move the element to its position in accordance with the real time spatial location data. Figure 23 shows the coordinate information that can be extracted from Revit for the components in this case study. The robot should rotate the object and place the items to the designed spatial position according to the 6 DOF data extracted from the BIM model. The approximate positioning method is on the basis of RFID and GPS sensor to create an on-site coordinate system. The robot or other advanced equipment can relocate the building component to the designated location. However, the accuracy of this technology is not high enough to ensure the quality and success of the construction, with a 50 mm level of accuracy. In order to increase the construction quality, accurate positioning is required using laser technique.

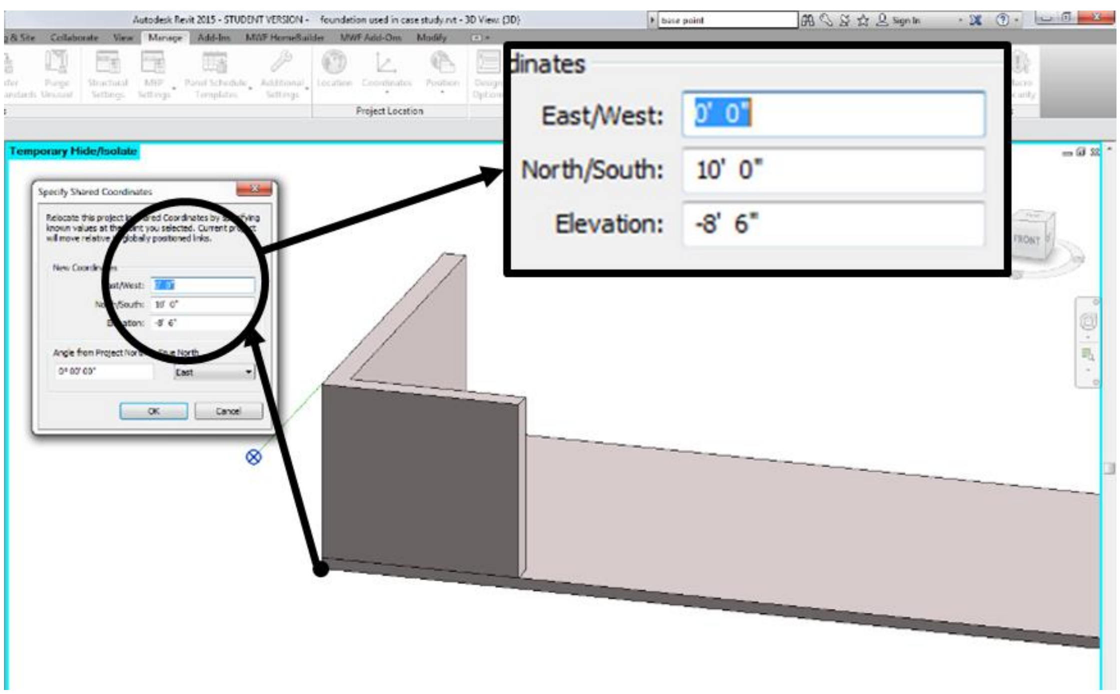

Figure 23. Point Coordinate Data

Another case study illustrates how these two levels of positioning methods function together for the on-site positioning

Case Study for Spatial Positioning

A simple example of the positioning of the automatic construction process is presented. This example is a structure consisted of two isolated footings, two concrete columns and one concrete beam as shown in Figure 24. The materials of this structure are all pre-cast concrete. Tags are created for each component.

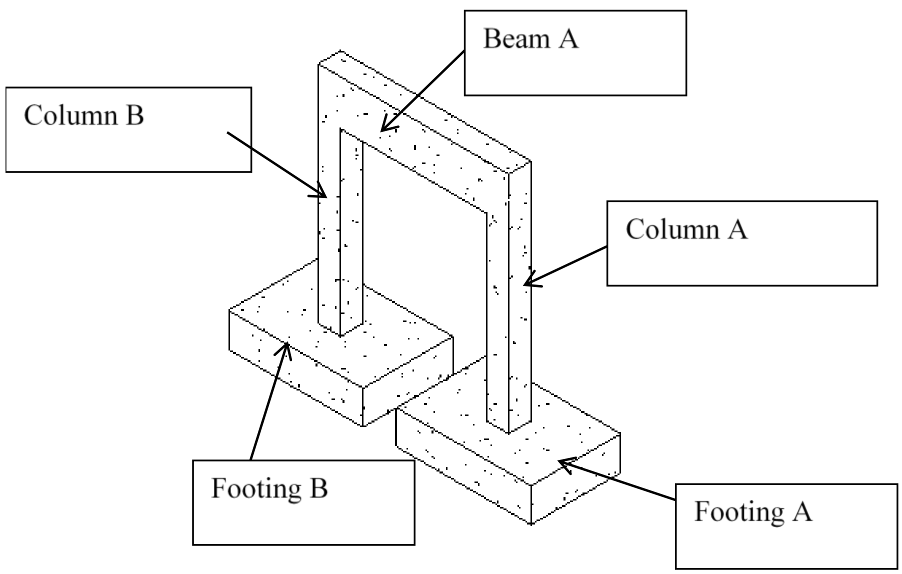

Figure 24. 3D Model of Case Study for Spatial Positioning

Two different stages are included in the positioning process which are approximate positioning and accurate positioning. The approximate positioning uses the

RFID and GPS technology. Each insertion point of each component has a relative coordinate.

Table 8 lists the coordinates of the insertion points of each building component.

Table 8

Data Used for Approximate Positioning

ID	Family and Type	Category	Insert Point
Footing A	Footing-Rectangular	Structural Foundations	(0’,0’,-1’-6”)
Footing B	Footing-Rectangular	Structural Foundations	(-7’-6’’,0’,-1’6’’)
Column A	Concrete-Square-Column	Structural Columns	(-2’-6’’,1’6’’,0)
Column B	Concrete-Square-Column	Structural Columns	(-10’,1’-6’’,0)
Beam A	Concrete-Rectangular Beam	Structural Framing	(-2’-6’’,1’-6’’,10’)

Figure 25 shows the insertion point for the second sample project.

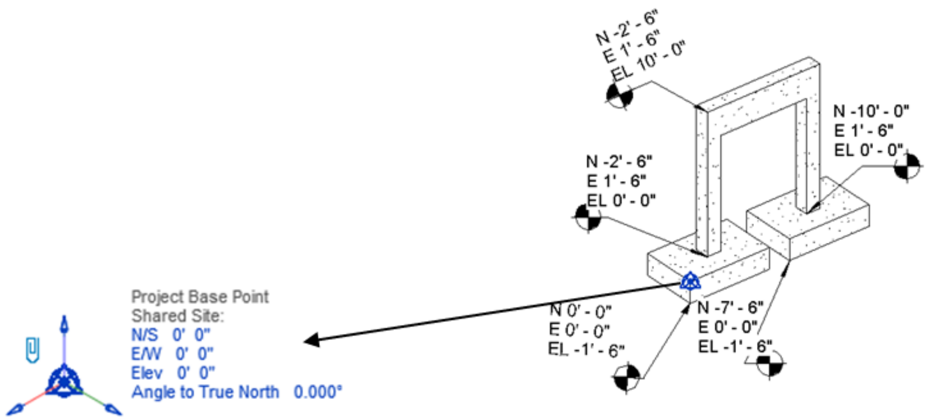

Figure 25. Insertion Points in On-Site Coordinates

In order to improve the accuracy of the installation, another technique using laser can be employed for location inspection. Laser technology (total station) can function as an accurate measurement of distance between objects which provides a high accuracy of positioning.

Laser tachymeters calculate the distance between the tags and the base points as a method of determine the accurate position of construction object. Figure 26 shows the potential setting out points and lines.

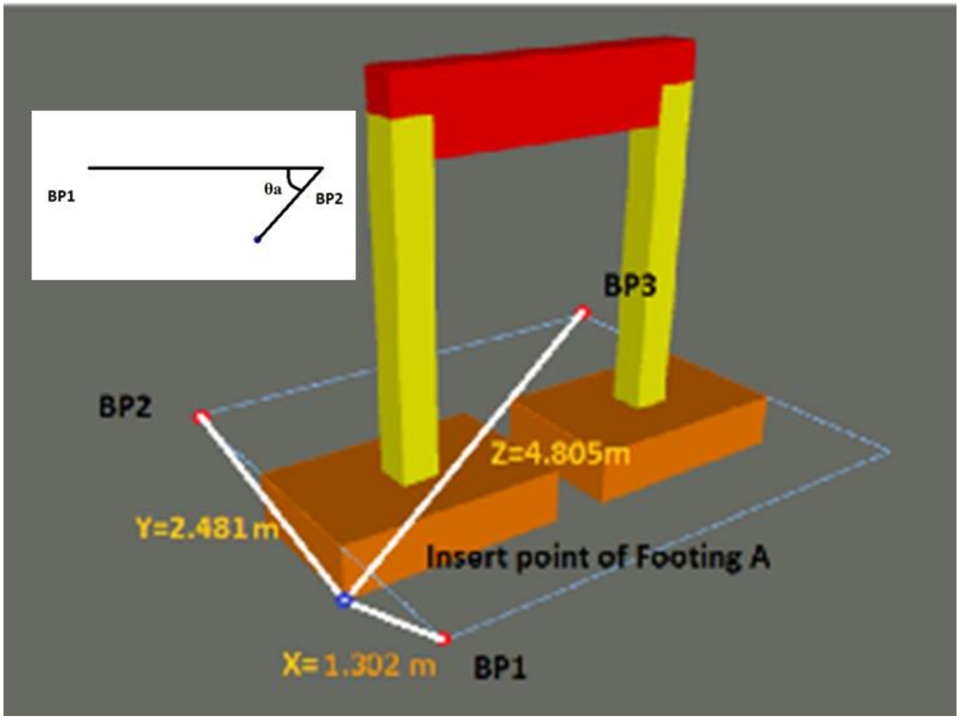

Figure 26. 3D Illustration of Project Site

Assume the distance from the insertion point of the building component to

- BP_1 (Base Point 1) is *x*
- BP_2 is *y*
- BP_3 is *z*.
- The angle between BP_1, BP_2 and the insert points θ_a.

As listed in Table 9, the position of the insertion point of each element can be calibrated by x, y, z and θa after the approximate positioning is finished. The function of θa is to adjust the insertion point that is above or below the elevation of the plane defined by BP1, BP2 and BP3.

Table 9

Data Used for Accurate Positioning

ID	Category	Insert Point (*x*, *y*, *z*)
Footing A	Structural Foundations	(1.302, 2.481, 4.805) θ_a: -
Footing B	Structural Foundations	(2.631, 3.374, 3.082) θ_a:-
Column A	Structural Columns	(1.841, 2.108, 3.894) Θ_a:0
Column B	Structural Columns	(3.487, 3.629, 2.250) θ_a:0
Beam A	Structural Framing	(3.561, 3.714, 4.945) θ_a:+

This method is more adaptive to simple outside building components and is on the level of spatial point. Indoor components positioning and calibration requires more base points in the indoor space or further development of space detecting and measuring technology. And instead of detecting the position of points, better methodology should be developed on the plane (2D) or space (3D) level. For example, high resolution camera system can create 3D model for as-built building. Comparing the as-built model and design model can check the quality and calibrate the building component. However, further development should be studied on how to improve the level of detail of the image and calculation speed. Too intensive calculation requirement and loss of details make this positioning technique immature.

CHAPTER V

CONCLUSIONS

Mankind has been constructing shelters since the first human raised branch to ward off the rain. Advances have occurred in the systems used for the development of rain protection for the average human family and also in the methods used to control the construction process. This thesis presents a study into the use of several novel techniques to advance the automatic control of construction. Any modern system that exhibits low productivity or low incremental increases in productivity provides a framework for the application of advanced planning and management controls to improve the work flow. Even if the cost of the work is not reduced, the work by Smith on the Wealth of Nations shows the savings in interest are sufficient motivation to seek faster methods of construction. The objective of the research is to consider the use of robotic systems to manage construction of buildings. The hypotheses are firstly that the construction processes can be defined and recorded by a newly developed computer program that utilizes Building Information Modeling. This has been demonstrated in this research work as true. The construction process can be presented in a computer language so that it is possible to perform construction under the management of computer software, which is also true.

Future research work should focus on developing a working model of this system.

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