

INTEGRATED INFORMATION MODELING OF CONSTRUCTION PROJECT PRODUCTIVITY

by

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ABSTRACT

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Integrated Information Modeling of Construction Project Productivity

Dissertation Directed by Professor Paul M. Goodrum

Construction productivity is of essence to the construction industry, since it directly or indirectly relates to the cost and schedule performance of a project. A construction project is a complex system, involving multiple participating parties and subsystems that comprise a plethora of components to enable a complete project to function. Construction projects are undertaken in an intricate and dynamic environment. Numerous factors, such as information, equipment, tools, materials, weather, supervision, safety, sequencing, congestion, can influence the productivity of a project's craft workers. A better understanding of how these and other factors impact a project can place both owners and contractors in a better position in predicting the performance of a project's outcomes. Currently, the lack of a robust framework to model and simulate the factors on a construction project's productivity compromises construction practitioners' ability to accurately assess the impact of these factors. However, Building Information Modeling (BIM) is a sophisticated platform that offers the potential to fulfill this need. BIM not only contains 3D graphical information of the various objects, but it also integrates data about the objects' attributes, such as cost, schedule, specification, and other information. The objective of this dissertation research is to provide a proof of concept in developing a framework to model productivity factors using BIM and lower level Critical Path Method (CPM) schedules to simulate the impact of these factors at a project level. As a starting point, the dissertation focus on structural steel erection projects only. This dissertation employs the model projects, computer

simulation, and quantitative analysis to test and validate the framework. This proposed dissertation follows a three-journal paper format. The first paper identifies a framework of using BIM to assess the impact of a type of steel innovation, steel quick connection system, on the structural steel erection construction phase of an office building. The second paper addresses the development of a framework to integrate BIM with CPM schedule to simulate the impact of temperature and humidity on the erection of the structural steel members of medical facility, with the consideration of situating the project in four different cities in the U.S. with different temperature and humidity scenarios. The third paper utilizes the framework developed in the second paper to simulate the impact of forecasted global warming trends on the earlier described project while the project is situated at various global locations between the years 2050 to 2099. This dissertation is a practical research effort. It contributes to the overall body of knowledge by developing a framework to develop prototypical models on which various factors affecting construction productivity, new construction methods and materials can be tested and their impact can be simulated and assessed. The concept of statistical analyses of the simulation results in the second and third papers can be used by construction practitioners to gain understandings about the factors under examination.

TO XIN, MY PARENTS, AND SISTER

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CHAPTER 1
INTRODUCTION AND BACKGROUND

PROBLEM STATEMENT

A construction project is a complex system, which encompasses different subsystems performing individual functions (Bertelsen 2003). Construction projects are unique by nature because of their distinctive functionalities and locations. Throughout the construction process, a typical project involves various parties (e.g. owner, contractors, designers, vendors, and regulators) meshed with other external factors (such as environmental, geological, and economical factors). From the perspective of systems, each construction activity can be viewed as a micro system. Each construction activity may be directly or indirectly interconnected with each other. Any change in a system can cause an immediate impact on a directly related system, or perhaps cause ripple effects to other systems. For example, delay in the conduit work in the wall studs immediately delay its successors, for instance, the insulation and enclosure of the walls. In order to accelerate the work, overstaffing and overtime are common methods for expediting a project, which may incur ripple effects, such as competing working areas with other trades and work area congestion. All intertwined and subtle relationships among the sub-systems make full comprehension of the mechanism of the whole system difficult.

Once in a while, debate around construction labor productivity has been very controversial. According to the U.S. Bureau of Labor Statistics, the labor productivity in the construction industry is declining at a compound rate of 0.48% during 1970 and 1998 (Teicholz et al. 2001). Nevertheless, other research efforts (Allmon et al. 2000) found that labor productivity has increased during 1980s and 1990s. However, compared to other industry sectors, it is readily admitted that the way people practice construction has not changed very much. The process of adoption of technological innovations in the construction industry is

relatively slow compared to other industries (Pries and Janszen 1995). Several reasons contribute to the fact:

- 1) The nature of business activities, processes, environment and organization associated with the construction industry makes it a high-risk industry (Akintoye and MacLeod 1997). In addition, business failure in the construction industry is highly associated with macro-economic environment (Arditi et al. 2000). Under current economy conditions, construction practitioners tend to be more conservative and less willingly to try unproved methods and technologies.
- 2) Since construction industry is a low-profit margin industry (Yeo and Ning 2002), lots of construction companies cannot afford investment in innovations.
- 3) The construction industry is a fragmented industry; 81.4% of companies have less than 10 employees (U.S. Census Bureau 2006), which compromises the industry-wide adoption of innovative construction methods, materials, and other technologies.
- 4) The construction industry lacks sophisticated scientific tools to assist construction practitioners to predict the outcome of a project before innovations or ideas are implemented.

Craft productivity is of essence to a construction project since it can be directly translated into construction costs (Hancher and Abd-Elkhalek 1998). A common way of recording craft productivity is to measure the work-hours required per unit of installed quantity. The ratio of actual work-hours to estimated work-hours is another common way of monitoring the project productivity. Typically, labor cost accounts for 30% of total construction costs, which is one of the largest constituents of the total costs (McNally and Havers 1967; McTague and Jergeas 2002). Failure to estimate and manage craft productivity may lead to cost overruns. However,

numerous factors affect craft productivity, varying from information, equipment, tools, materials, rework, congestion, sequencing, weather, supervision, plant status, safety, size of components, specification, work content, design features, to work scope (Thomas and Sakarcan 1994).

Among the mentioned factors, weather is a significant factor when it comes to the construction industry. It is reported that 50% of the activities involved in construction are affected by weather (Benjamin and Greenwald 1973; Shahin et al. 2010). Even though weather is a factor beyond a project's control, accurate evaluation of its impact on a project would benefit construction management decisions, including bid estimating, construction schedule planning, and evaluation of alternative plan implementation due to weather effects.

The construction industry faces another long-existing challenge, the shortage of robust systematic tools to model craft productivity in order to assess the impact of influencing factors on productivity and thereby predict their overall impact at a project level. To some extent, the Construction Industry Institute (CII) Model Plant provides such solution. Originally, the CII Model Plant (Scherer and Tucker 1986) was intended to meet the need for industry-wide construction productivity measurement. The model plant is a typical representation of a petrochemical plant with a total construction cost ranging from \$75-85 million dollars (in 1985 dollar value), consisting of nine major components: fractionation unit, tank farm, compressor unit, turbine generators, underground piping, pipe bridge, and others. In addition to its function as standard productivity measurement, the CII Model Plant can also be used as a platform to test technological innovations, constructability issues, and other new construction concepts or methods to understand the impact. The CII Model Plant has not been frequently updated since its development in 1986. The old media, such as microfiche and floppy disk that were used to record the data limited efficient data processing and transfer. The estimates of work hours were

performed at the level 3 of the project's work break down structure (WBS), by system, not at the assembly level. In addition, the lack of sound supportive tools made an in-depth study of the interconnecting relationships among different construction activities impossible. Thus, the accuracy of the evaluation of new ideas or concepts' impact performed on the model plant was questionable, since too many improper assumptions were made in some studies.

In these regards, it is vital for the industry to develop a framework that is able to conduct various construction productivity studies. This dissertation does not necessarily provide an ultimate solution, but instead it develops a proof-of-concepts to illustrate how BIM systems can be used to simulate productivity performance of construction. With the advancement and proliferation of building information modeling technology in the construction industry, the dissertation focuses on how to exploit the advantage of BIM to conduct construction productivity studies in an automated and more accurate manner than traditional venues.

DISSERTATION STRUCTURE

This dissertation comprises five chapters. The first chapter presents the problem statement, the structure of the dissertation, research objectives, and scope of research. Chapters 2, 3, and 4 follow a format of journal papers. Each chapter can be served as a journal paper that will be submitted to peer-review academic journals. In this regard, each chapter from Chapters 2 to 4 contains an abstract, introduction and background, points of departure, research methodology, results and discussion, conclusions and recommendations, and references. Each paper answers a research question. Given that each chapter can be considered as a standalone paper, some inevitable overlaps might be observed among these chapters. In particular, chapter 4

is an extension of chapter 3, and it uses the framework developed in Chapter 3. The final chapter, Chapter 5, is the conclusions, which mainly states the overall findings of the dissertation research, contributions to the overall body of knowledge, limitation of the studies, and path forward for future research studies. Finally, the appendices include the Visual Basic for Application (VBA) code for the automated computation algorithm throughout the dissertation and some additional results of a few analyses that were not included in the dissertation's actual report.

RESEARCH SCOPE

The main goal of this dissertation research is to develop a process that integrates 3D CAD Models, physical attributes of CAD elements with construction productivity, and a crew level CPM schedule to simulate the impact of jobsite factors on craft workers' productivity at a project level. This dissertation research aims to develop prototypical models that, to some degree, function like the CII Model Plant against which new construction materials, concepts, and various productivity factors can be tested and analyzed. However, this dissertation used two available structural steel erection projects: one is a five-story office building built in Santa Clara, California, and the other is the University of Kentucky Albert B. Chandler Hospital Pavilion project. The University of Kentucky Albert B. Chandler Hospital Pavilion project will be referred as the UK Hospital project in later chapters. There are several reasons for selecting the steel structure project as the base model project. First, the CIMsteel Integrated Standards(CIS/2) is a steel-specific data standard, so that the well defined scheme of this standard can ensure successful data exchange among different BIM software packages. Currently, other BIM data

standards involving timber, concrete, and electrical are yet to be matured and have not widely implemented in the industry. Second, steel erection activities are performed outdoors, which are highly susceptible to weather conditions; it meets the research purpose under consideration. Third, steel structural erection activities usually happen prior to other trades' work, and productivity losses due competing workface with other trades could be minimized, which is less intervened by other trades during construction. Thus, the variability of productivity losses due to other factors can be reduced. Fourth, steel construction is usually on a project's critical path, so a better understanding of the factors that affect steel productivity will have a direct impact on a project's schedule performance.

It should be noted that there are numerous factors influencing construction productivity since a construction project situates in a dynamic environment and different factors impacting craft productivity coexist on a project. However, modeling all of the possible factors and understanding the mechanism of various factors' effect on productivity can be difficult and cumbersome. This dissertation purposefully selected the steel trade as the scope of this study to minimize productivity variability that would be otherwise possibly caused by other trades and factors. When it comes to the study of the impact of a factor, simplifying a model by ruling out other factors is a common practice. As such, this research limits to studying the impact of one productivity influencing factor at a time.

Together with safety and quality, cost and schedule are the most critical criteria used to measure project performance. However, this study focuses on the impact on project performance in terms of work hours and project duration, because the data on these indicators are easier to obtain and measure compared to data on safety and quality.

RESEARCH OBJECTIVES

Figure 1- 1 provides the conceptual overview of the research objectives. The primary objective of this research is to develop a robust approach to simulate construction productivity influencing factors at a project level by using a building information modeling (BIM) system.

The primary objective can be broken down into multiple secondary objectives, as follows:

1. Develop a novel framework of using BIM to analyze the construction productivity changes as a result of steel innovations on a structural steel erection project;
2. Integrate BIM model and CPM schedule to simulate impacts of temperature and humidity at a project level; and
3. Investigate the potential impact of forecasted global warming trends on construction productivity at various global locations based on the framework developed in the second secondary objective.

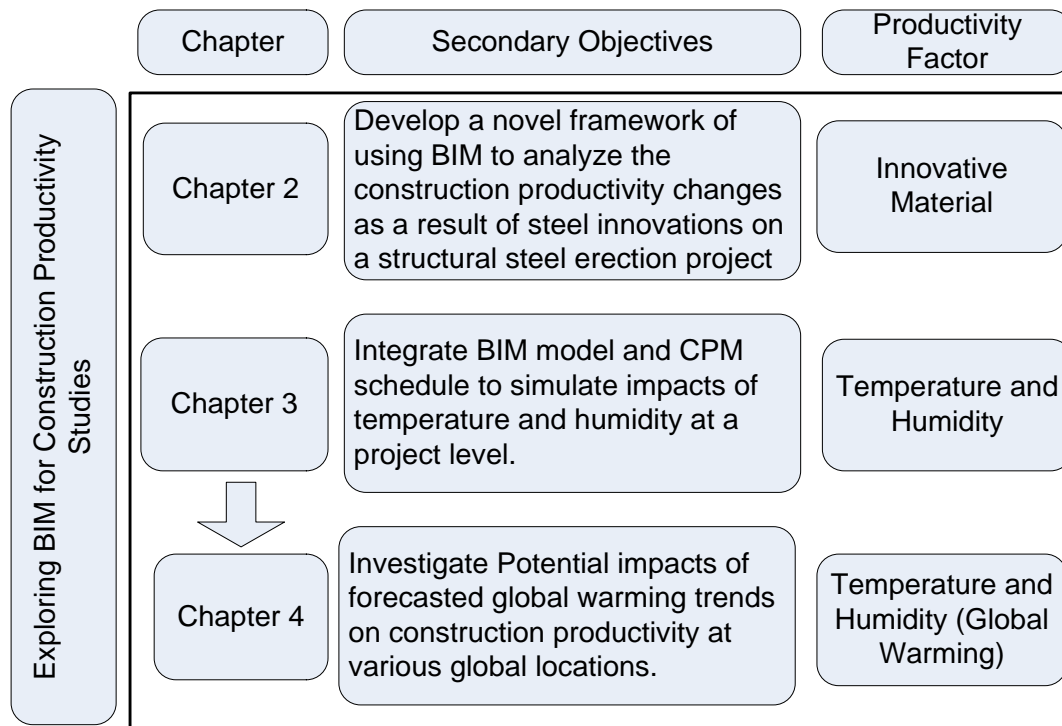


Figure 1- 1. Conceptual Overview of Research Questions and Dissertation Structure

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CHAPTER 2
ASSESSING PRODUCTIVITY IMPROVEMENT OF STEEL QUICK
CONNECTION SYSTEMS(SQCS) IN THE STEEL CONSTRUCTION
INDUSTRY USING BUILDING INFORMATION MODELING (BIM)

AUDIENCE: Practitioners and Researchers

ABSTRACT

Current execution of building information modeling (BIM) is still at its infant stage, especially in the construction sector. The primary areas of BIM use are limited to pre-project planning, visual presentation, clash detection, and shop-drawing processes (Azhar 2011). This paper explores the proof of concept of utilizing BIM as a simulation platform to perform construction productivity analyses considering alternative construction materials. The analyses presented herein utilize the integration of a five-story office building's structural steel BIM model with a unit rate labor productivity and steel attributes database to examine the productivity impact of adopting a structural steel quick connection system (SQCS). Two design and construction alternatives were analyzed: one with a conventional (weld and bolt) steel connection system and the other with SQCS, which utilizes an interlocking beam-column and beam-beam connection mechanism. The results of the analyses show that the SQCS required 43% fewer work hours than the conventional systems did on the model project. The implications of using SQCS are discussed as opposed to the conventional steel and presented with a 4D schedule animation comparison. The paper contributes to the overall body of knowledge by developing a BIM-based approach to simulate the effect of construction materials on productivity at a project level. It also presents the promising schedule impact of the SQCS identified by the research effort.

KEYWORDS: Building Information Modeling, Quick Connection system, Steel Construction, Labor Productivity, 4D Schedule Animation

INTRODUCTION

The construction industry as a whole has been branded as a slow technology adoption industry (Mitropoulos and Tatum 1999). Besides the nature of the fragmentation (Ahmad et al. 1995; Nam and Tatum 1992) and high risk (Akintoye and MacLeod 1997) associated with the industry, the lack of robust tools to assess the impact of productivity influencing factors and thereby predict their overall impact on a project can be a hindrance to the industry in adopting new innovations, either in the form of a new technology, method, or strategy. Often times, estimates of productivity gains due to new innovation implementation are based as a percentage of current productivity performance in specific construction activities. However, these estimates are typically so narrow in scope that it becomes difficult to extrapolate the estimated improvement to a project's bottom line in terms of total costs or total hours required to build the project. Anecdotal evidence suggests that construction firms find the latter estimation of a process' impact to be a more convincing argument in adopting a new innovation.

The Construction Industry Institute's (CII) model plant developed in 1985 was intended to be utilized as a platform for construction productivity studies, especially among the CII research efforts (Scherer and Tucker 1986). Originally, the model plant was developed to meet the need of benchmarking industry productivity. This model plant included a cost estimate, man-loading curves, and construction schedules for a hypothetical petro-chemical refinery plant with a total construction cost ranging from 75 to 85 million dollars (1985 dollar value), consisting of 9 major components of a plant: fractionation unit, tank farm, compressor unit, turbine generators, underground piping, pipe bridge, and others (Scherer and Tucker 1986). In addition to its primary use of productivity benchmarking, it is also used as a test bed to assess the impact of new equipment technologies (Guo and Tucker 1993), examine the workforce training and

utilization strategies (Borcherding et al. 2004; Brandenburg et al. 2006; Burleson et al. 1998; Castañeda et al. 2005; Gomar et al. 2002; Srouf et al. 2006; Wang et al. 2010), constructability issues, and new construction materials and methods. However, the model plant was not digitally recorded, which prevents efficient data exchange and automated analyses. Moreover, the lack of sound supportive tools made in-depth productivity studies difficult.

However, the emerging technology, building information modeling (BIM), could help the industry to rethink the problem and find a better solution to it. BIM is known for its rich information, automated process, integrated platform, and seamless information exchange. Taking advantage of the preeminent features of BIM, this paper presents a usage of BIM as a tool to perform construction productivity studies.

BACKGROUND AND LITERATURE REVIEW

Though the concept of BIM has been around since 1970s (Eastman and Fisher 1974), its use in the construction industry as a whole is still in the infancy stage (Fortner et al. 2008). A couple reasons are offered to explain the slow development and adoption of BIM: 1) inadequate capability of computer graphics in the earlier years inhibits the research and development in this technology (Eastman et al. 2011); and 2) the lack of industry-wide standards makes interoperability a prominent issue. A study commissioned by the National Institute of Standards and Technology, NIST GCR 04-867 (NIST 2004), reported that waste due to inadequate interoperability in the U.S. capital facilities industry tallies up to \$15.8 billion per year. Recently, with the burgeoning development and significant price drop of computer hardware, the momentum of BIM software development among the major CAD software vendors accelerated.

In addition, leading organizations, such as the buildingSMART AllianceTM, formerly named International Alliance for Interoperability (buildingSMART 2012), and National Institute of Standards and Technology (NIST) are collaborating with extensive research efforts, software vendors, and industry organizations to promote the development of industry-wide standards. BIM has become increasingly popular among the Architecture, Engineering, and Construction (AEC) Industry in the recent years. However, BIM is primarily adopted by large-scaled and complex projects, and its usage is not exploited to the greatest extent (Fortner et al. 2008).

The adoption of BIM in the ACE industry is on the rise. According to a survey of the Construction Management Association of America (CMAA 2007) conducted in 2007, 35% of the surveyed building owners experienced BIM on some of their projects. A similar survey conducted by McGraw-Hill Construction (2008) in 2008, 46% of the surveyed owners indicated having used BIM on more than 30% of their projects. Azhar (2011) collected cost and benefits data on 10 projects involved with BIM from the Holder Construction Company (HCC), a general contracting company, and performed a return on investment (ROI) analysis as a result of the company utilizing BIM on their projects. The ROI of BIM on different projects ranged from 1.4 to 399 with an average of 16.3. As the evident benefits of BIM are realized in the industry, coupled the initiatives made by government agencies and other research institutes, the BIM adoption rate will continue growing. For instance, the office of chief architect of the General Services Administration's(GSA)'s Public Building Services (PBS) made BIM mandatory on all new projects undertaken in the fiscal year of 2006 to improve the whole delivery process (Hagan et al. 2009). Research efforts in universities also played a vital part in facilitating BIM execution in the AEC industry. For instance, research efforts both at Indiana University (IU) and Pennsylvania State University published a BIM execution plan for the industry in 2009 (Mayo et

al. 2012). In 2010, the BIM software vendor, Autodesk, took IU's execution plan as the template and crafted their first Project BIM Execution Plan with respect to Revit software suites (Mayo et al. 2012).

Through literature review, the research effort summarize related research studies on BIM with a focus on applications at specific stages of a project's life cycle, including design, construction, and operation and maintenance stages. As the research effort have observed, applications have been primarily limited to building and industrial projects and less on infrastructure projects. At the conceptual design stage, BIM is primarily used for sustainability analysis (Azhar et al. 2011; Cho et al. 2010; Krygiel and Nies 2008; Stumpf et al. 2009) including the aspects of building orientation evaluation, building envelope optimization, daylight analysis, renewable energy alternative evaluation, sustainable material analysis, and site and logistics management. For the construction stage, Goedert and Meadati (2008) proposed a framework of integrating construction process documentation with BIM models. Ibrahim and Krawczyk (2004) presented an approach in conveying desired CAD objects from an offsite server to the construction site through the web by using extended markup language (XML) to complete the query for the needed data. Lu and Korman (2010) performed case studies on two modular construction projects using BIM models, and identified that BIM demonstrates its advantages in design coordination, walk-through animation, and clash detections, particularly in mechanical, electrical, and plumbing (MEP) coordination. To enable an exhaustive clash detection in MEP design coordination, Leite et al. (2009) identified data items that need to be modeled. Current BIM applications focus more on pre-construction and construction stages. However, because of the rich information repository, BIM can be integrated with facility management platforms as well. A cases study of adopting BIM for facility management was

performed on the Sydney Opera House. The findings showed that the availability of facility management applications seamlessly integrated with BIM is challenging, because the BIM standards are not fully implemented in the realm of facility management; however, the enterprises towards integration have started (Innovation 2007). In order to fully integrate BIM with facility management, standards and data exchange that describe the necessary information for facility management included in models are vital. The Construction Operations Building Information Exchange (COBIE) tends to help address this issue. COBIE was developed by the Corps of Engineering Research Lab (CERL), and it is a standard template of construction operation and maintenance information that is handed over to an owner at the end of a project's construction phase (Sabol 2008).

POINT OF DEPARTURE

This dissertation research departs from the current body of knowledge by exploring the opportunity of using BIM as a tool for construction productivity analyses. Despite the versatility BIM possesses, current applications of BIM in the AEC industry are limited to pre-project planning, visual presentation, clash detection, and shop-drawing processes (Azhar 2011). Current literature addresses the most prevalent applications of BIM and envisions the future use of BIM. However, few research efforts address the subject described herein. The BIM systems aim to capture all of the information in a digital 3D model accessible to project stake holders throughout a project's lifecycle, from the pre-project planning stage to decommission (NBIMS 2013). Making best use of BIM largely depends on how to exploit and manipulate the information contained in a BIM model to maximize the success of a project.

SCOPE AND OBJECTIVES

The objective of this paper is to develop a prototypical framework for using BIM to perform construction productivity studies in assessing innovative construction technologies, ideas, and methods. Specifically, for this research, the scope of this dissertation research is limited to steel construction for three reasons. First, this research used CIS/2 as the standard format for data exchange between different BIM applications. Both IFC and CIS/2 are the popular open standards implemented among the industry for the sake of interoperability of different data formats developed by proprietary software vendors. IFC is a schema with universal data structure that describes all of the information of a building throughout various stages of a project from feasibility study, engineering, construction, to operation and maintenance, and with a purpose of ensuring information exchange among different phases (buildingSMART 2012). For the time being, the breadth and flexibility of the schema associated with IFC leaves room for errors and is not sufficient for achieving full interoperability between BIM tools (Eastman et al. 2010). On the contrary, CIS/2 is targeted to the steel industry and provides flexible, independent views of the model data for design, detailing, scheduling, and fabrication (Khemlani 2005). Despite its smaller scope, CIS/2 is easier to implement on an industry-wide level than IFC. Second, currently available BIM software application that is capable of performing the described study mainly targets the industrial construction market, which by itself involves a large quantity of work in the steel and piping trades. Last, structural steel erection is typically on the critical path of a project; schedule performance on steel erection matters the overall schedule.

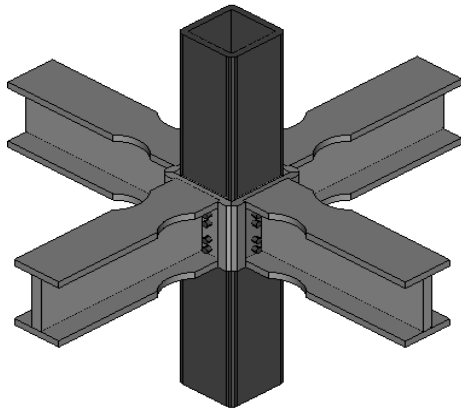
The concept of this research could be applied to any study of the same nature, which is intended to evaluate construction innovations' impact on a project prior to its construction phase.

For this particular case, a type of newly emerged steel quick connection system (SQCS) was identified as an innovation to be tested on a BIM model. The model project that was used in this research is a previously built steel structure for a five-story commercial office building located in California, and once again only the steel structure was examined in this study. Thus, it was possible to assess the impact of using SQCS on the project's bottom line in terms of total work hour and labor cost savings on the model project.

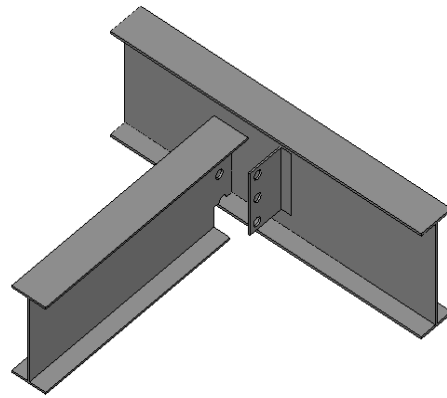
RESEARCH METHODS

Steel Quick Connection Systems

A type of SQCS developed by ConXtech was selected for the study. Because of its inherent seismic, blast and progressive collapse resistant characteristics, the system is ideally used on commercial, office, hospital, military, school, parking, data center, and industrial facilities (under 15 stories). The structural frame built with the identified SQCS comprises hollow structural section (HSS) columns, wide flanges beams, and three types of innovative connectors: one gravity connector, and two different moment connectors (Figure 2- 1). The usage of two types of moment connectors depends on the bay spacing of a structure. One of them can be applied on structures with the range of bay spacing from 8 to 20 feet; and the other can be used on structures with bay spacing up to 65 feet. Compared to the conventional connection systems, the described SQCS eliminates conventional cut, fit or field weld. This system enables every beam-to-column connection to be designed as a moment connection to create a rigid frame space that eliminates braces, thus reduces the amount of steel used compared to conventional structural steel systems.



Moment Connection



Gravity/Shear Connection

Figure 2- 1. The Steel Quick Connection System

Model Project

The model project used here is a five-story commercial office building located in Santa Clara, California, with a total square footage of 152,000 square feet. In particular, only the steel structure of the model project is being utilized here. The bay spacing of the entire steel structure ranges from 28 to 38 feet (Figure 2- 2). It is a LEED Silver certified Class A office building. The total installed quantity of steel members with SQCS amounts to 677 tons in weight. The structure of the office building was initially designed with conventional steel. Having recognized the potential benefits of adopting SQCS systems, the owner later decided to redesign the structure with SQCS. Fortunately, the owner's decision allowed the research effort to have a direct comparison between conventional and SQCS applied on a real project.

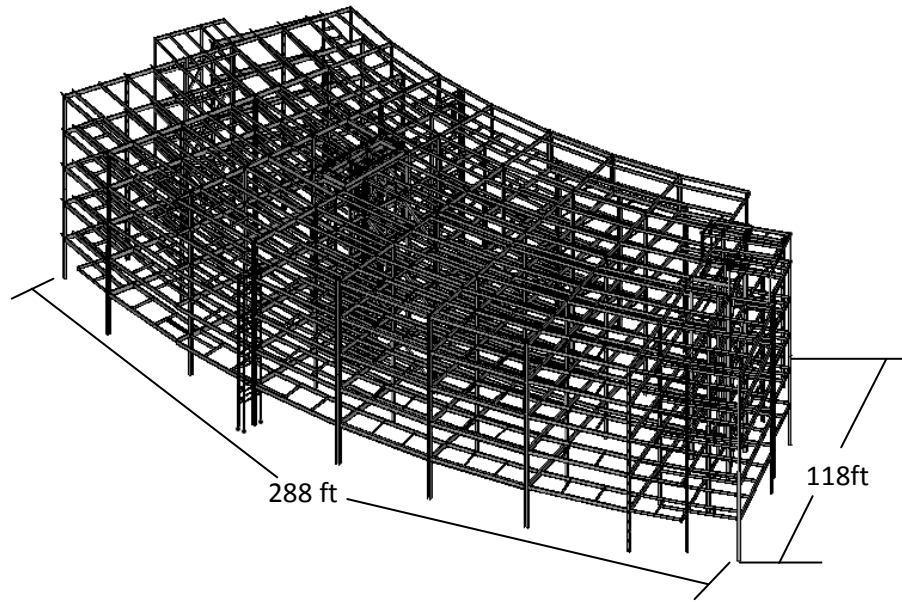


Figure 2- 2. Isometric View of the Model Project

Modeling Techniques

One of the important procedures involved in modeling was to differentiate steel members involving SQCS from the conventional steel members, which is essential to performing the analyses. The reader should note that the SQCS could not be applied to all of the model's steel members; short cantilever steel members still rely on the conventional systems because of economic purposes, which is yet another advantage gained in the use of BIM for this analysis.

A steel member can be differentiated by its cross-sectional size, grade, and function (e.g. column, beam, brace, joist, etc.). This research only involves structural steel; therefore, CIMSteel Integrated Standards CIS/2(NIST 2014) targeted for steel trades was used for information exchange among the BIM applications employed. In the CIS/2 Standards, piece marks are used to distinguish the steel members with different functions, sizes, and lengths. Table 2- 1 shows part of the quantity take-off spread sheet extracted from the model project in CIS/2 format. Steel members with the same length, size, and function were assigned the same

piece marks. By default, the functions of the steel members are usually listed as beam, column, brace, and joist, among other configurations. Since the SQCS has different types of connectors for both gravity and moment connections, the function needed to reflect the possible varied connections. Thus, Beam-bgg, Beam-bmm, and Beam-bgm were used to differentiate the steel beams with varied types of connectors. Beam-bgg denotes a beam with gravity connectors at both ends; Beam-bmm represents a beam with moment connectors at both ends; and Beam-bgm represents a beam with gravity connector at one end and moment connector at the other. The angle steel and cantilever beams used the conventional connection systems and thus were denoted with default function naming "Beam."

Table 2- 1. Partial Quantity Take-off Steel Members from CIS/2 formatted Model

	Qty	Mark (Bold-main)	Size (Link to Material List)	Length (Ft-In)	Grade	Unit Wgt* (Lbs)	Total Wgt* (Lbs)	Function	Mark (Bold-main)
20	1	A-20	L5X5X3/8	9 1/8	A36	31	31	Beam	A-20
21	1	A-21	L5X5X3/8	3 7/16	A36	12	12	Beam	A-21
22	1	A-22	L5X5X3/8	6 1/4	A36	21	21	Beam	A-22
23	5	B-1	W24X55	5-1 13/16	A992	930	4648	Beam-bgm	B-1
24	5	B-2	W24X55	1-11 7/16	A992	352	1761	Beam	B-2
25	2	B-3	W24X55	10.84	A992	1955	3911	Beam-bgm	B-3
26	3	B-4	W24X55	10.86	A992	1960	5880	Beam-bgm	B-4
27	9	B-5	W18X35	10-9 3/8	A992	1238	11142	Beam-bgg	B-5
28	6	B-6	W14X22	5.22	A992	376	2259	Beam-bgg	B-6
29	4	B-7	W14X22	5.19	A992	375	1498	Beam-bgg	B-7
30	6	B-8	W24X55	10-7 3/16	A992	1912	11474	Beam-bgg	B-8
31	4	B-9	W24X55	10-6 7/8	A992	1908	7631	Beam-bgg	B-9
32	5	B-10	W24X55	1.52	A992	275	1374	Beam	B-10
33	4	B-11	W24X68	6-9 7/8	A992	1522	6089	Beam-bgm	B-11
34	6	B-12	W24X55	6-9 7/8	A992	1231	7387	Beam-bgm	B-12
35	23	B-13	W24X68	8.39	A992	1871	43043	Beam-bmm	B-13
36	100	B-14	W24X55	8.39	A992	1514	151365	Beam-bmm	B-14

Model Conversion and Processing

In order to compute the required work-hours to build the model project, tying construction related information to model objects is essential. Two major processes were involved: one was model conversion, and the other was model processing. Figure 2- 3 illustrates the mechanism of the model conversion and processing in a BIM application, Bentley's ConstructSim, that was used for the described research. ConstructSim is a sophisticated system with the support of MS SQL server and Access database enabling a powerful data manipulation and report.

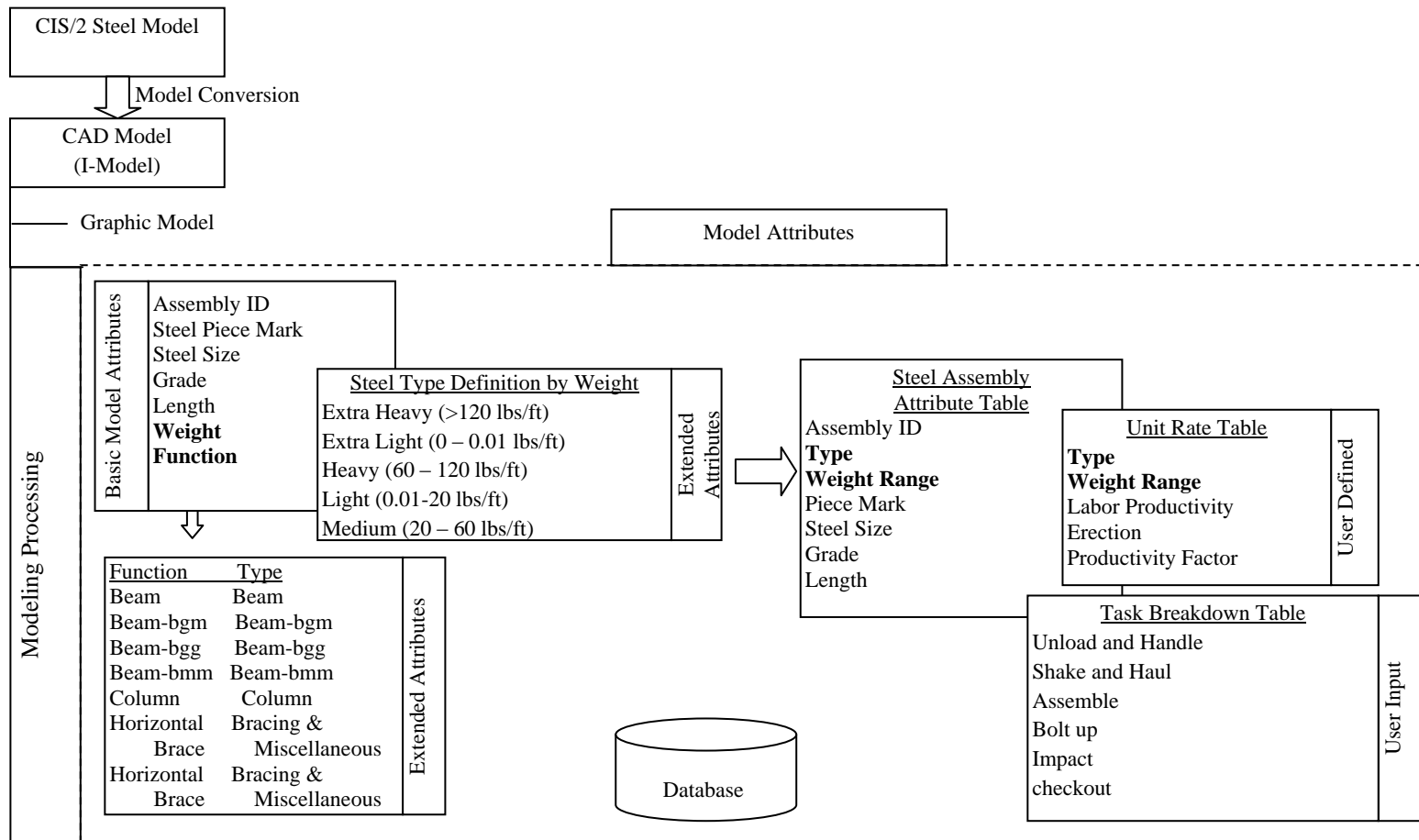


Figure 2- 3. Mechanism of Model Conversion and Processing within the BIM application

The main goal of model conversion is to convert a model with a known data structure to another model with a new data structure that can be understood by the BIM software installed on users' local computer. For this research effort, model conversion involved transferring the information contained in the CIS/2 file into an I-model data format developed by Bentley.

Model processing with ConstructSim involves two sub-processes: assigning attributes and task processing. The process of assigning attributes is to append construction related information to model objects through a series of relational database tables (Figure 2- 3). The information of work hours was assigned to each steel member by matching the table headers of Type and Weight Range, which appear in both steel assembly attributes and productivity unit rate tables. Task processing breaks down each assembly's erection activity into 6 sub-activities, including: (1) unload and handle, (2) shake out and haul, (3) assemble, (4) bolt up, (5) impact, and (6) checkout. However, the details of the schedule for this model project would not reach the level of the sub-activities.

Data Collection

The purpose of field data collection is to attain the data in regard to productivity improvement as a result of applying SQCS. The identification of the described steel innovation is also part of the Construction Industry Institute's Research Team (RT) 252's efforts. RT 252 randomly sampled 9 projects including 3 commercial, 3 multi-family residential, and 3 industrial projects that adopted SQCS, and field data were collected from each of them. To calculate the productivity improvement using the innovative versus conventional steel connection systems, it is ideal to obtain participating companies' historical productivity data. However, due to the restriction of access to such data, this research effort utilized unit rate productivity data obtained

from RS means (RSMeans 2012), a cost estimating manual, as the baseline productivity for conventional connection systems. In Table 2- 2, the readers should note that the work hours and quantities listed under the SQCS only recorded the amount of the steel members involving SQCS. Field data showed that the unit rate labor productivity difference between the SQCS and conventional systems ranged from 48.47 to 76.25% (Table 2- 2). The equations used for the computation were listed in the headers of Table 2- 2. The productivity factor is defined as the ratio of unit rate of SQCS to the base line productivity obtained from RSmeans. This could be interpreted as SQCS involving steel members only using 23.75 to 51.53% of installation time required by conventional systems. The unit rate productivity described herein is defined as the ratio of work-hours to the installed quantities. It should be noted that total labor hours savings in percentage on a project as a whole could not achieve the numbers listed in the column (5) of Table 2- 2, since the SQCS only saves installation time for beam-to-column and beam-to-beam connections involved with SQCS and does not alter the construction methodology for columns and regular beams' erection. Therefore, simply using a number from the table as a multiplying factor and applying uniformly to the entire project would result in loss accuracy of the simulation. This also offers the reason for employing BIM to perform the analyses in the described research.

Table 2- 2. Unit Rate Productivity Difference between Conventional and SQCS

		Unit Rate			Time Savings		Productivity
		Conventional		SQCS			Factor
Projects		(1)	(2)	(3)	(4)=(3)/(2)	(5) =[(1)-(4)]/1×100%	(6)=(4)/(1)
		Unit Rate (wh/Ton)	Work hour	Quantity (Ton)	Unit Rate (wh/Ton)	%	%
Office	Medical	9.80	1,352	429	3.15	67.86	32.14
	Data Center	9.80	1,440	619	2.33	76.25	23.75
	General	9.80	2,464	824	2.99	69.51	30.49
Residential	Military	8.73	2,760	670	4.12	52.85	47.15
	High-density1	8.73	3,951	1,121	3.52	59.64	40.36
	High-Density2	8.73	9,240	2,619	3.53	59.59	40.41
Industrial	Training Tower	6.09	20	11	1.84	69.79	30.21
	Portable Tower	6.09	180	127	1.42	76.70	23.30
	Water Processing	6.84	1,550	440	3.52	48.47	51.53

Unit Rate Productivity Table

Work hours required to build this model project with the conventional system and SQCS were established through referencing a unit rate productivity table. Table 2- 3 shows the unit rate productivity table for SQCS. In this case, the research effort used the unit rate productivity from RSMeans (RSMeans 2012) cost data as the baseline productivity. Again, the productivity factor is defined as the ratio of the productivity under the consideration of SQCS to the baseline productivity (i.e. productivity for conventional steel). For the conventional design model, a productivity factor of 1.0 was uniformly applied to all of the steel members. For the design model with SQCS, a productivity factor of 32.14%(0.3124) was applied to beams (i.e. Beam-bgg, Beam-bgm, Beam-bmm) with SQCS, and 100% (1.0) was applied to the rest of the steel members since productivity gains can only be attained on the beams with SQCS, and SQCS does not alter the process of steel column erection.

Table 2- 3. The Unit Rate Productivity Table for Steel Structure Erection

UR_ID	Component Type	Activity Type	Unit	Unit Rate	Productivity Factor	Weight Range	Type
H.1.1.1	STEEL_ASSEMBLY	Erect	TN	8.889	1	Extra Light	Beam
H.1.1.2	STEEL_ASSEMBLY	Erect	TN	8.889	1	Light	Beam
H.1.1.3	STEEL_ASSEMBLY	Erect	TN	8.889	1	Medium	Beam
H.1.1.4	STEEL_ASSEMBLY	Erect	TN	8.889	1	Heavy	Beam
H.1.1.5	STEEL_ASSEMBLY	Erect	TN	8.889	1	Extra Heavy	Beam
H.1.4.1	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Light	Beam-bgg
H.1.4.2	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Light	Beam-bgg
H.1.4.3	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Medium	Beam-bgg
H.1.4.4	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Heavy	Beam-bgg
H.1.4.5	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Heavy	Beam-bgg
H.1.5.1	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Light	Beam-bgm
H.1.5.2	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Light	Beam-bgm
H.1.5.3	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Medium	Beam-bgm
H.1.5.4	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Heavy	Beam-bgm
H.1.5.5	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Heavy	Beam-bgm
H.1.6.1	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Light	Beam-bmm
H.1.6.2	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Light	Beam-bmm
H.1.6.3	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Medium	Beam-bmm
H.1.6.4	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Heavy	Beam-bmm
H.1.6.5	STEEL_ASSEMBLY	Erect	TN	8.889	0.3214	Extra Heavy	Beam-bmm
H.1.2.1	STEEL_ASSEMBLY	Erect	TN	8.889	1	Extra Light	Bracing And Miscellaneous
H.1.2.2	STEEL_ASSEMBLY	Erect	TN	8.889	1	Light	Bracing And Miscellaneous
H.1.2.3	STEEL_ASSEMBLY	Erect	TN	8.889	1	Medium	Bracing And Miscellaneous
H.1.2.4	STEEL_ASSEMBLY	Erect	TN	8.889	1	Heavy	Bracing And Miscellaneous
H.1.2.5	STEEL_ASSEMBLY	Erect	TN	8.889	1	Extra Heavy	Bracing And Miscellaneous
H.1.3.1	STEEL_ASSEMBLY	Erect	TN	8.889	1	Extra Light	Column
H.1.3.2	STEEL_ASSEMBLY	Erect	TN	8.889	1	Light	Column

4D Schedule Analysis

The purpose of 4D schedule analysis was to visually compare the schedule performance as a result of using SQCS versus conventional systems on the model project. The mechanism behind the 4D schedule animation is to link model objects with the project schedule by matching the task name in a schedule with the name of the objects in a BIM model. The objects in a model can be referred to as a collection of individual objects. In this study, a “work package” was the task unit used when creating a schedule for the simulation purpose. A work package represents the worth of a crew's work in a week, ranging from 400-1000 work hours depending on the crew size (CII 2012). The research effort used the following assumptions when creating the schedules:

- a 10-worker crew working 5 days and 10 hour a day was used on the project;
- each work package was assigned with approximately 500 work-hours work equivalent to the amount of work performed by the described crew in a week (5 days); and the last packages may deviate from 500 work-hours at a larger scale;
- interruptions due to weather, material supply, rework, and other issues were not considered in the scheduling;
- Saturdays and Sundays were the only non-working days; and
- the activities were performed in a sequential manner and on critical paths for both the conventional steel and SQCS.

The project is assumed to start November 4, 2013. Two schedule simulations scenarios with respect to with/without SQCS were presented in parallel, allowing better comparison of schedule performance at different points in time (Figure 2- 4).

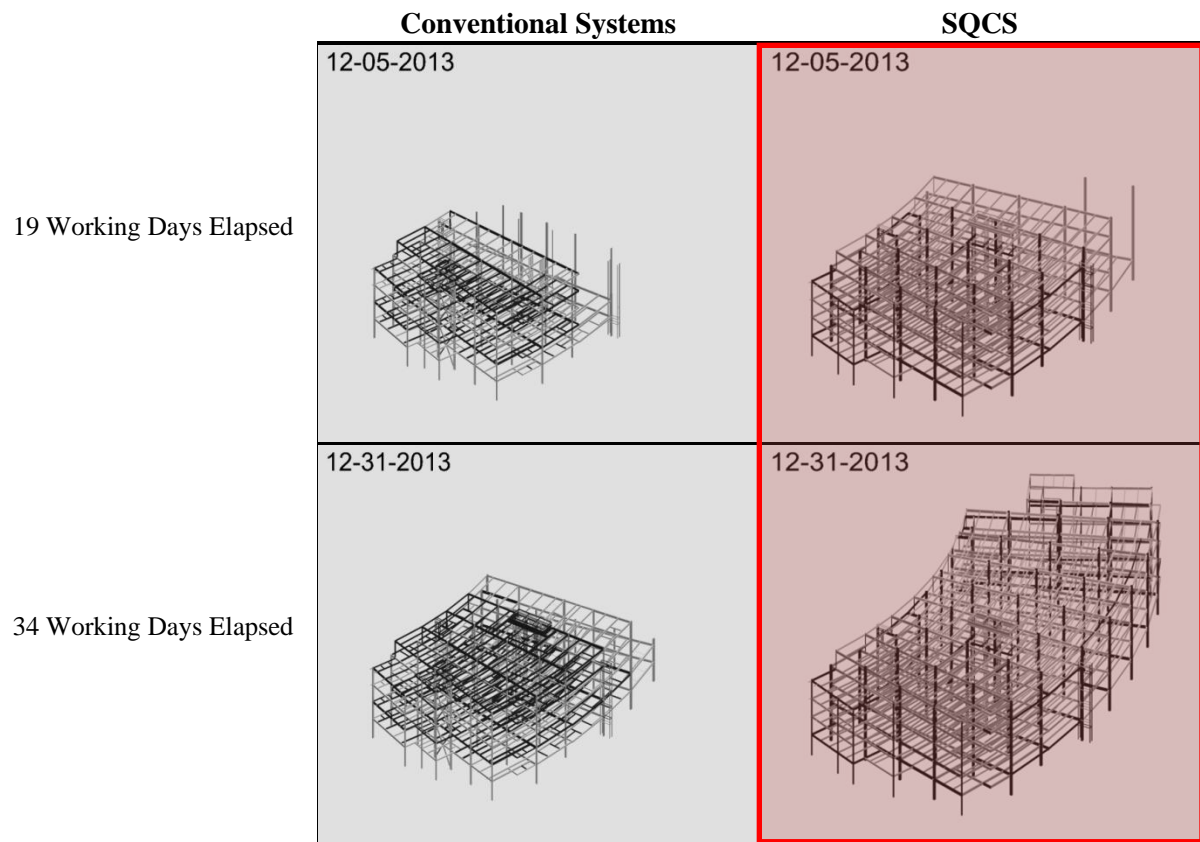


Figure 2- 4. Comparison of Schedule Performance Simulation Conventional vs. SQCS (at two different time points)

RESULTS AND DISCUSSIONS

Table 2- 4 summarizes the comparison between the scenarios with conventional systems and SQCS. There is not much difference in total tonnage of the steel required for both designs. The results show that, under the conventional steel erection procedure, the total computed work hours required to build the model project amounts to 5,832 work-hours; while by incorporating SQCS into the process, only 3,314 work-hours were needed to build the same structure. This represented savings of 2,518 work-hours. In other words, implementing SQCS on the model project could save 43% of the work-hours required by the conventional connection systems.

Based on the assumptions, conventional steel erection process could complete the project in 59 working days, while adopting SQCS could complete the project in 34 working days, 25 working days fewer than the former scenario. As shown in

Table 2- 4, 12 work packages were created when using conventional steel. While using SQCS, the number of work packages was reduced to 7. To clarify the economic benefits of SQCS in terms of labor costs, the research effort assumed a bare labor cost of 47.36\$ per hour obtained from RSMeans(RSMeans 2012). There is also a significant labor cost saving observed.

Table 2- 4. Summarized Comparison between Conventional vs. SQCS Systems

	Conventional	SQCS
Tonnage	656	677
Work Hours	5,832	3,314
Labor Costs Bare Cost (\$47.36/hr)	276,203	156,951
Working Days	59	34
Work Packages	12	7

The structure with SQCS experienced a significant work hour and labor cost reduction in steel erection. This productivity gain is a result of simplified steel erection processes by eliminating on-site welding and bracing installation as opposed to conventional steel. As mentioned earlier, the SQCS allows rigid moment connection for every bay spacing to create a rigid frame space, thus could use smaller column sizing as opposed to larger columns required by conventional steel. However due to this specific project's location in an earthquake active zone, rigorous seismic requirements were imposed on the design with the SQCS. Therefore, the benefits of reduction in steel tonnage were not observed on this project. The structure with the SQCS experienced a significant work hour and labor cost reduction in steel erection. However, the SQCS requires authorized manufacturers to produce the steel. The process of producing

SQCS is more stringent than conventional steel because of the smaller tolerance allowed for onsite erection. Presumably, the productivity of manufacturing SQCS is lower, and the price of SQCS is higher than conventional steel. Therefore, labor hour savings on on-site erection is partially resulted from the longer hours spent on manufacturing process. According to the interview with some personnel from the vendor of the described system, they felt, for this particular project, the total estimated project costs of steel structure with SQCS is comparable to conventional systems. Nevertheless, the SQCS possesses significant advantages over conventional systems when schedule is the key driver of a project.

Other considerations should be taken as well when adopting SQCS, such as logistic issues. Currently, authorized manufacturers of the described system are located in west coastal regions. This might incur expensive transportation costs if a project is located afar from manufacturers. However, as this product gains more popularity, there would be more authorized manufactures spreading across the U.S. As shown in Table 2-3, despite a significant decrease in the number of work packages with SQCS, on average more pieces of steel members were included in a work package, a worth of a crew's work in a week. This could impose more stress on material supply, material handling, lay-down and staging area, and other material logistics. Nevertheless, the detailed information as a result of BIM-based productivity analyses empower project planners to have better materials, site, and equipment planning. The BIM-based productivity analyses and automated work packaging renders the detailed information that is adequate for the planning at a crew level. The generated work package report allows planners to foresee the itemized quantity of steel needs to be installed in a period of time. Based on this information, planners would have the knowledge of when the materials should be delivered and

whether the capacity of the current lifting equipment matches the improved speed of steel erection due to SQCS, as well as the knowledge about the proper size of lay-down yard area.

Table 2- 3. Comparison of Work Packages Conventional vs. SQCS

Conventional System			SQCS		
Work Package	# of Steel	Wh	Work Package	# of Steel	Wh
#1	165	500.2	#1	118	500.2
#2	128	500.3	#2	215	500.7
#3	163	500.0	#3	243	499.5
#4	132	500.0	#4	149	500.4
#5	186	499.7	#5	115	500.3
#6	98	499.5	#6	135	499.4
#7	108	499.9	#7	238	313.9
#8	80	499.8			
#9	95	500.0			
#10	115	499.9			
#11	139	500.1			
#12	186	333.0			
Average (pcs/500-hour Work Package)	137		Average (pcs/500-hour Work Package)	183	

Note: Mean difference in number of steel members per work package between two systems is 46, with a P-value =.12

However, in terms of schedule performance, it should be reminded that the many external factors can affect a project's progress and hence delay the schedule. For instance, weather, material supply, construction errors, and foundation progress could all cause delays. These factors were out of the scope of this study.

CONCLUSIONS AND RECOMMENDATIONS

Differentiating with current common applications of BIM in the AEC industry, this paper proposes a framework of using BIM to perform labor productivity studies, based on an case of evaluating of construction alternatives, which provides an approach to predict the impact of a new process on a project's bottom line that can be established by referring to companies'

historical data for traditional methods. This study took a type of SQCS as an example and tested the practicality of the proposed framework. The results indicate that SQCS outperformed conventional systems on the model project in terms of schedule, with a 43% of time saving. This research contributes to the overall body of knowledge by providing an extended utilization of BIM for labor productivity studies. The framework for this study can be extended by examining other productivity affecting factors, such as weather, overcrowding, and overtime. The limitation of this research is that, currently, it is only applicable to steel construction because of yet-to-be-matured BIM standards and industry-wide implementation of the standards. However, with the emergence of wide-spread BIM standards and extensive implementation among the industry, similar studies can be performed in all other trades with the same concept. In the real business world, schedule performance is only one evaluation criterion, and cost is another factor that is always evaluated before the implementation of a new process. Especially, on cost-driven projects, economic evaluation is a significant review process. A further study on costs is recommended if project stakeholders want to determine whether SQCS should be adopted on their projects or not. With the adoption of SQCS, the quantities of installed steel components within the same period of time outnumber the quantities when convention systems were adopted, which could impose stress onto the efforts associated with material supply, equipment selection, and the layout of staging and lay down areas. Nevertheless, the BIM-based approach described in this paper is capable of providing the information that is needed for site, materials, and equipment planning on a weekly basis.

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CHAPTER 3
INTEGRATION OF BUILDING INFORMATION MODELING AND
CRITICAL PATH METHOD SCHEDULES TO SIMULATE THE IMPACT OF
TEMPERATURE AND HUMIDITY AT THE PROJECT LEVEL

AUDIENCE: Practitioners and Researchers

ABSTRACT

Steel construction activities are often undertaken in an environment with limited climate control. Both hot and cold temperatures can physically and psychologically affect construction workers, hence decrease their productivity. Temperature and humidity are two factors that constantly exert forces on workers and influence their performance and efficiency. Previous research studies have established the relationship between labor productivity and temperature and humidity. This paper is built on the existing body of knowledge, and develops a frame work of integrating building information modeling(BIM) with a lower level critical path method (CPM) schedule to simulate the overall impact of temperature and humidity on a healthcare facility's structural steel erection project in terms of total man hours and duration required to build the project. This research effort utilized historical weather data of four cities across the U.S., with each city having workable seasons all year around, to test if various project starting dates and locations of a project could significantly impact the project's schedule performance. It was found that both varied project start dates and locations significantly contribute to the difference in the work hours required to build the model project and that the project start date and location have an interaction effect. This research effort contributes to the overall body of knowledge by providing a framework that can help practitioners better understand the overall impact of a productivity influencing factor at a project level, in this case temperature and humidity, in order to facilitate better decision making.

Key Words: Labor Productivity, Steel Construction, Building Information Modeling, CPM Schedule, Temperature, Humidity, Weather

INTRODUCTION

Construction labor productivity is affected by many factors, and weather is one of them since almost 50% of the construction activities are affected by weather (Benjamin and Greenwald 1973). Both hot and cold temperatures beyond craft workers' comfort may influence construction workers both psychologically and physiologically and result in productivity losses. As a result of prolonged exposure to freezing or subfreezing working conditions, workers may suffer from health problems such as frostbite, trench foot, and hypothermia (OSHA 2013). In addition, prolonged exposure to hot working environments may result in psychological effects such as lethargy, irritability, and restlessness, and physiological effects, such as heat stroke, heat cramps, and heat exhaustion, may occur (Hancher and Abd-Elkhalek 1998). OSHA sets forth tips regarding how to protect workers from possible health threats because of the cold or heat. One of the common considerations to combat cold and heat is to include more break time into a work cycle. Consequently, craft workers' tool time (i.e. the time spent on actual work) decreases.

Among the climatic factors, temperature and humidity are the two of the most critical factors (Koehn and Brown 1985) that influence craft workers' productivity, since they exist ubiquitously and exert their effect on craft workers. Understanding the temperature and humidity effect not only affords project management a better construction schedule, but also enables a better bid with a more accurate estimate taking into consideration of the comprehensive effect of weather.

Modern commerce involves retail operations engaging capital project delivery of structures with common construction footprints in multiple geographic locations. Retailing

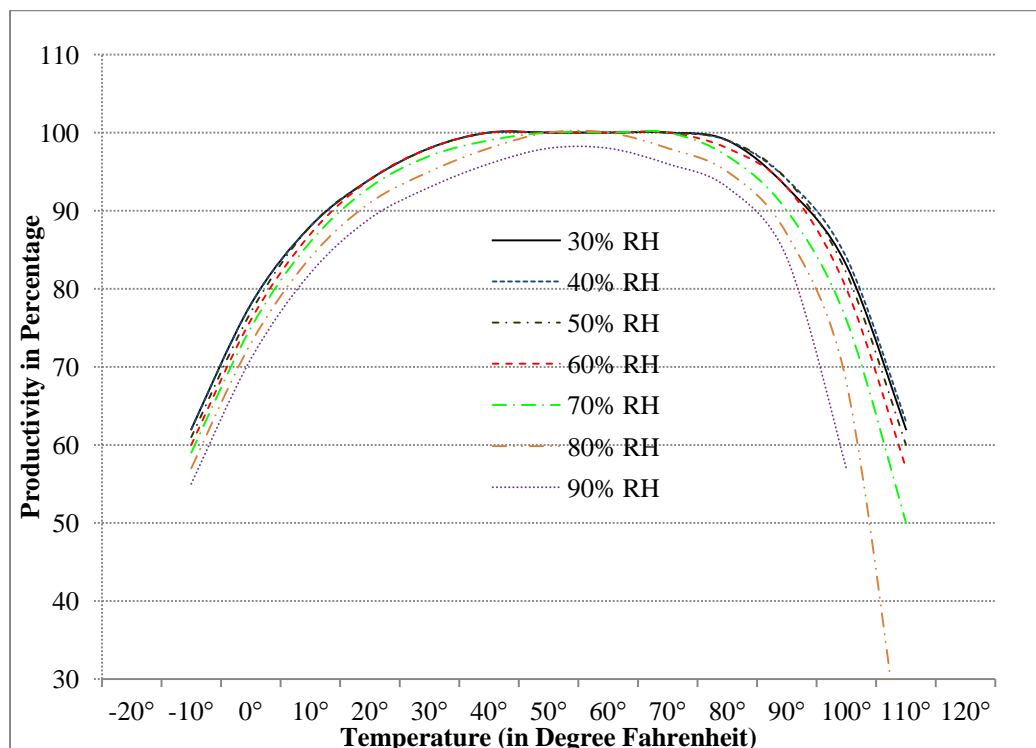
stores, such as Wal-Mart, Target, K-Mart, and Home Depot, often build their facilities with a similar design of the buildings across the country. A multitude of criteria may be involved in the decision of selecting business locations, such as regional scale of economy, infrastructure, and capital investment. One of the major components of the capital investment can be the costs of buildings. Labor productivity directly correlates with the total costs of a project. Therefore, it is vitally important for a decision maker to understand the impact of factors that affect labor productivity. The objective of this study is to develop a framework that is able to assess the impact of a productivity factor at a project level. For this particular case, temperature and humidity are the focus.

LITERATURE REVIEW

During 1970s and 1980s, a number of research studies (Grimm and Wagner 1974; Koehn and Brown 1985; NECA 1974; Thomas and Yiakoumis 1987) examined the labor productivity (measured by productivity factor or productivity in percentage) relative to temperature and humidity. Productivity factor is often defined as the ratio of the optimal baseline labor productivity to actual labor productivity at a designated temperature and humidity. It should be noted that the labor productivity is defined as work-hours per unit of installed quantity; a smaller measure indicates a better productivity. Therefore, a productivity factor less than 1 indicates that an optimal baseline labor productivity is better than the actual labor productivity. However in other studies, the productivity has been at times defined inversely to what is described above. Below is a summary of the four studies.

The National Electrical Contractors Association (NECA 1974) found that humidity is a significant factor affecting productivity when working at both elevated and low temperatures. NECA (1974) analyzed the productivity of two electrician journeymen performing the same duplex receptacle installation in an environment where temperature and humidity can be controlled. Source: **National Electrical Contractors Association (1974)**

Figure 3- 1 summarizes the journeymen's productivity at 30 to 90 percent relative humidity at various temperatures. Findings indicate that productivity significantly decreases at temperatures above 80 °F and below 40 °F; humidity plays a very important role at elevated temperatures; and that in extreme cold conditions, temperature is a more significant factor than humidity.



Source: **National Electrical Contractors Association (1974)**
Figure 3- 1. Journeymen Productivity at 30 to 90 Percent Relative Humidity

Grimm and Wagner (1974) performed a study on 51 workers involved in standard masonry wall panel erection and examined the productivity at temperatures 40 to 100 °F with relative humidity 20 to 100%. The results were plotted among a series of isopleths as shown in Figure 3- 2.

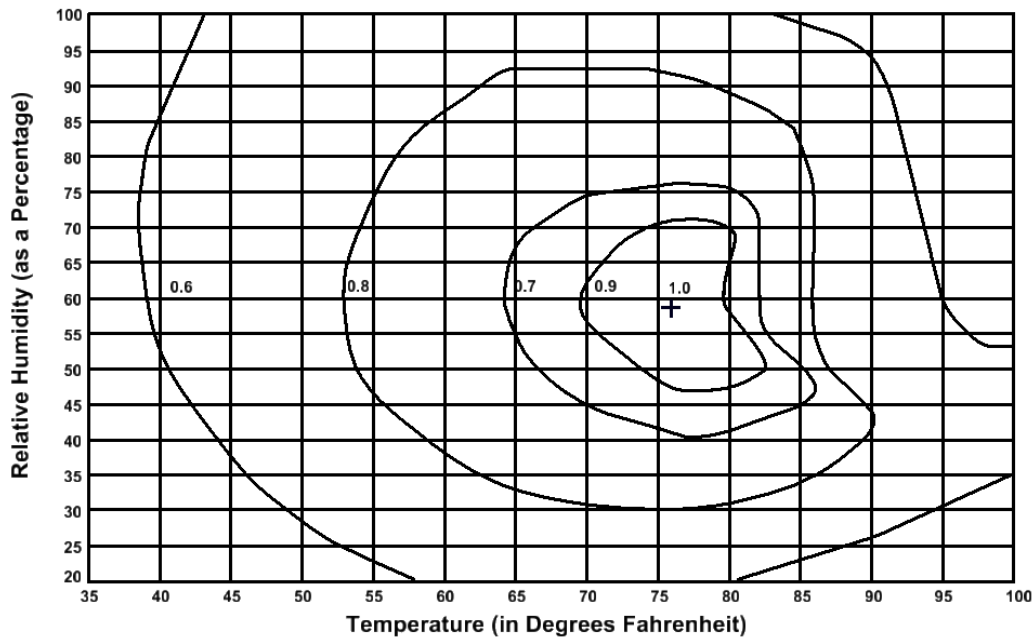


Figure 3- 2. Mason Productivity Relative to Temperature & Humidity

Koehn and Brown's (1985) model collected a total of 172 productivity data points, ranging from -40 °F at 90% relative humidity (RH) to 125 °F at 10% RH among steel, masonry, electrical, carpentry, and labor occupations. A linear regression model for construction productivity factor was then developed as a function of both temperature and relative humidity. Two equations were derived; Equation 3-1 is applicable to cold or cool weather from -20 °F to 50 °F, and Equation 3- 2 is applicable to warm or hot weather from 70 °F to 120 °F.

Equation 3- 1

$$F_c = 0.0144T - 0.00313H - 0.000107T^2 - 0.000029H^2 - 0.0000357T.H + 0.647$$

Equation 3- 2

$$F_w = 0.0517T + 0.0173H - 0.00032T^2 - 0.0000985H^2 - 0.0000911T.H - 1.459$$

Where, F_c denotes the productivity factor under cool or cold weather; F_w denotes productivity factor under warm or hot weather; T denotes temperature in degree Fahrenheit; and H denotes relative humidity in percentage.

Equation 3 and 4 were normalized as a function of their respective maximum values, i.e. percent of standard efficient operations. To obtain a realistic and smooth transition, productivity at 60 and 70 °F was taken as unity (1). The results of construction productivity as function of temperature and relative humidity were tabulated in Table 3- 1.

Table 3- 1. Construction Productivity (as a Percent of Standard Efficient Operation) as Function of Temperature and Relative Humidity

Temperature (°F)	Relative Humidity (%)									
	5	15	25	35	45	55	65	75	85	95
-20	0.28	0.27	0.25	0.22	0.18	0.13	0.05	-	-	-
-10	0.44	0.43	0.42	0.40	0.38	0.34	0.29	0.21	0.10	-
0	0.59	0.58	0.57	0.56	0.54	0.52	0.49	0.44	0.36	0.23
10	0.71	0.71	0.70	0.70	0.69	0.67	0.65	0.62	0.58	0.50
20	0.81	0.81	0.81	0.81	0.81	0.80	0.79	0.77	0.75	0.71
30	0.90	0.90	0.90	0.90	0.90	0.89	0.89	0.89	0.88	0.87
40	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
80	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.95	0.93
90	0.95	0.95	0.94	0.93	0.92	0.90	0.88	0.85	0.82	0.78
100	0.81	0.81	0.80	0.79	0.77	0.74	0.71	0.67	0.61	0.54
110	0.58	0.58	0.58	0.57	0.55	0.51	0.47	0.41	0.32	0.21
120	-	0.28	0.28	0.28	0.25	0.21	0.15	0.07	-	-

Thomas and Yiakousmis (Thomas and Yiakoumis 1987) investigated the relationship between labor productivity and air temperature and humidity. A multiple regression analysis technique was performed on the data collected from multiple commercial projects, and the following equation (Equation 3- 3) was derived:

Equation 3- 3

$$PR = 9.448 + 0.0518T_a - 2.819 \ln(T_a) + 3.89 \times 10^{-37} e^{(R_h)}$$

where PR denotes the performance ratio defined as the ratio of actual labor productivity to estimated baseline labor productivity, which is the inverse of productivity factor described in other studies. The reliability of Equation 3- 3 is limited by the range of temperature from 12 to 82 °F.

Overall, these models differentiate each other by taking different construction activities and various parameters into consideration, and the productivity data were collected at the different ranges of temperature. Some models collected more data at the warm conditions than cold conditions. However, they all reflect similar trends. Most of the research studies in this area agree on the premise that temperature and humidity have a very influential effect on construction workers' productivity.

POINT OF DEPARTURE

This study builds upon the existing knowledge from the literature review regarding the relationship between temperature and humidity and labor productivity. In addition, the research effort integrates building information modeling (BIM), a critical path method (CPM) schedule, and temperature and humidity data to simulate the impact of climatic effects at the project level. This study distinguishes itself from other studies by examining the climatic effect at the project level instead of focusing on the activities at a task level through the utilization of BIM, which allows the integration of construction productivity information with the 3D model and automates the process of computing work hours required to build the project.

SCOPE OF RESEARCH

The primary objective of this study is to develop a frame work that integrates the BIM model with unit rate construction productivity and CPM schedules to simulate the impact of temperature and humidity at a project level. The secondary objective of this study is to use historical weather data from four cities in the U.S. to test how project locations and project start dates at different seasons could affect the project's schedule performance. The author readily admit that other weather factors, such as precipitation, could also affect a project's schedule. However, precipitation highly depends on the season, geographic characteristics such as mountains, rivers, and topography, and other atmospheric factors. Furthermore, there is not an established relationship between the physical amount of precipitation and construction productivity performance. In order to focus on the impact of temperature and humidity only, the research effort ruled out other factors that could potentially affect construction schedules. To reduce the possible impact of other factors that could complicate the results of the described study, the process of city selection also took special considerations that will be discussed in the later section of the paper. This dissertation project only focuses on the structural steel erection activities of a project based on the following reasons: 1) steel erection activities are undertaken outdoors and subject to the influence of temperature and humidity; 2) the steel activities are the upfront activities, usually given high priority, and less likely to be interfered by other trades, and thus reduces the noise effect attributed to other factors; 3) structural steel construction usually resides on a project's critical path and its performance matters the entire project's schedule; and 4) the BIM standard for steel, CIMsteel Integrated Standards(CIS/2), is a steel trade specific standard with a smaller scope and easier to implement by most of the software vendors, and thus

reduces occurrences of errors during the process of data exchange between different BIM software applications (NIST 2014).

RESEARCH METHODS

The section describes the basic techniques and steps involved to accomplish the overall research objectives. The following workflow describes the steps that formulate the framework of the research:

- 1) Convert the CIS/2 formatted BIM model into a virtual construction model integrated with baseline unit rate labor productivity information, assigning work hour information to model objects;
- 2) Select a proper productivity model that describes the labor productivity relative to temperature and humidity;
- 3) Design a data download interface to obtain the historical daily weather data from the Weather Underground (WU) ranging from the year 1961 to 2010;
- 4) Based on the selected labor productivity model describing the relation to temperature and humidity, calculate the mean productivity factor for each day;
- 5) Develop a baseline schedule of the project according to the construction activity sequences that took place on the actual project;
- 6) Develop a schedule simulation interface using VBA built in Excel to integrate the CPM schedule with man power sources and productivity factors considering the temperature and humidity effect to automate the process of simulating temperature and humidity effect on the model project;

7) Use the simulation interface and input data to generate simulation results in terms of work hours and project durations required to build the project under various project locations and project start dates; and

8) Perform statistical analyses on the generated simulation results.

Building Information Modeling (BIM) Technology

BIM is an emerging technology in the architecture, engineering, and construction (AEC) industry. Its application covers the whole spectrum of a project's lifecycle from the conceptual stage, to pre-project planning, engineering, construction, operation and maintenance, and decommission stage. The National BIM Standards (NBIMS 2013) define BIM as, *"A digital representation of physical and functional characteristics of a facility. As such it serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its lifecycle from inception onward."* Eastman et al. (2011) presented the six key characteristics that a matured BIM technology entails : 1) Digital; 2) 3D; 3) Dimensionally and quantitatively measurable, and query-able; 4) Containing and communicating design intent, building performance, constructability, and including sequential and financial aspects; 5) Accessible to all the stakeholders through interoperable and intuitive interfaces; and 6) Usable throughout the whole lifecycle of a facility. In this study, BIM was primarily used as the platform for building information integration and automation.

Why BIM?

BIM plays an important part in this research. It appears that CPM schedule analyses could perform the described study since we only focus on one trade. However, developing a construction schedule in a BIM environment integrated with labor productivity rates allows schedule planners to develop a more realistic and crew level schedule, which is the accurate level

that a general CPM schedule could not reach. Current CPM scheduling software has not included labor productivity in their packages yet. For this study, only one trade is examined. However if a model would involve multiple trades, developing a schedule with the assistance of BIM integrated with labor productivity would show tremendous benefits. Particularly, for young schedulers, developing a schedule in a BIM environment with 3D graphical representation of an actual building and the work hours associated with model objects would help them better visualize the sequence of the construction activities and properly allocate resources required for each activity.

Model Project Characteristics

Considering the validity of the research results, the model of University of Kentucky's Albert B. Chandler Hospital Pavilion project was used. It is a healthcare facility project recently completed at the University. Turner Construction Company was the construction manager of the project. The entire project started in 2009 and completed in 2011. It has a basement and a five-story podium along with two eight-story towers on top, with a total area of 1.2 million square feet. The complete project has 512 private patient rooms and 28 operating rooms in the surgical suites. The structure of the five-story podium and basement is reinforced concrete. The rest of the structural frame was constructed with structural steel. For this research, only the steel structural model was used.

Virtual Construction Model Processing

The process of the virtual construction model processing is to seamlessly transfer the information of the engineering model into a BIM application platform and append extra information that complement the construction phase. Figure 3- 3 illustrates the workflow of

building the virtual construction model for the purpose of this dissertation research. Two major processes were involved: model conversion and model processing.

The goal of the model conversion is to map the data of a neutral formatted model to a data structure format that is unique to a BIM software installed on a users local machine. This research effort used Bentley's ConstructSimTM, to build the virtual construction model. Since structural steel is the focus of this study, the CIS/2 data format was used during the process of data exchange between different BIM applications.

Model processing involves assigning attributes that are related to the construction stage to the model objects. For this dissertation research, the model processing involved assigning the work hour information to individual steel members through a series of relational SQL database tables and cross-referencing a unit rate construction productivity table (Figure 3- 3). A secondary processing, task processing, was also involved in the model processing in which an erection activity was broken down into several steps. Users can specify the percentage of time spent on each step based on company practices or field observations. For this dissertation research, the steel installation process was broken down into erection and detailing. Based on the work log of the project, the average time spent on erection accounts for 75% of the total installation time, and detailing accounts for 25% of the time. In this particular case, erection included the activities from unloading material to initial bolt-up, while detailing included leveling, plumbing, final tightening, welding and quality assurance. At the end of this process, the construction task for each steel member was broken down into two sub-activities, and work hours required for each sub-activity were populated.

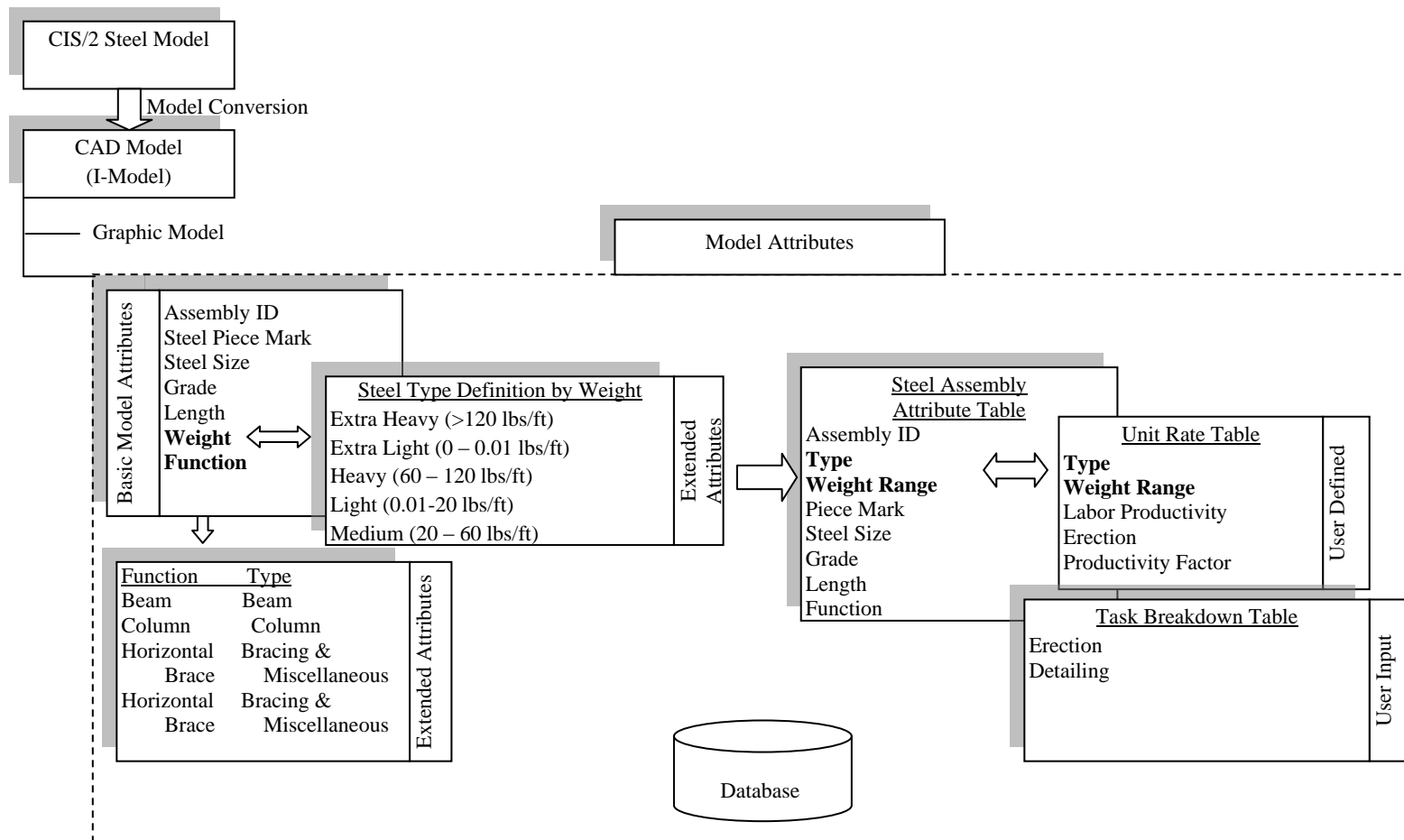


Figure 3- 3. Mechanism of Model Conversion and Processing within the BIM application

Source of Unit Rate Labor Productivity

This research utilized labor productivity information to estimate the work hours required to build the project, and subsequently develop the corresponding construction schedule. Ideally, using a company's historical productivity data would be preferable. However, construction companies treat their craft productivity data as confidential information. Thus, the unit rate labor productivity information was obtained from RichardsonTM Construction Estimating Standards. RichardsonTM has a 47-year history and has been recognized as reliable standards for cost estimating in the construction industry (Richardson 2013). Richardson was not originally purposed for productivity studies, but it records the information of unit rate labor productivity. The unit rate productivity described herein is defined as work hours per unit of installed work. A lower measure indicates a better productivity. The unit rate productivity shown in RichardsonTM is collected among the work performed under the following conditions(Richardson 2013):

- i) Contractors are familiar with the project jobsite conditions;
- ii) The work is being performed under proper supervision;
- iii) The workers are skilled enough to perform the job;
- iv) Adequate craft workers are provided;
- v) There is no obstructed access to jobsite with a 50-mile radius of an urban area;
- vi)The work is being performed within a comfortable temperature range;
- vii) A week does not exceed 40 hours of work;
- viii) The work is being performed within the scope of the Work Accounts;
- ix) Engineering information such as project plan, drawings, specifications, and manuals are properly prepared and available; and

x) Time for incidentals that are necessary to perform the work are considered. The incidental time includes, but are not limited to: start-up and wind-down time, supervisory instruction, scheduled and non-scheduled breaks, personal time, housekeeping time at the end of shift, tool box meeting, material handling, getting tools and equipment, tool adjustment and minor repair.

The steel members are categorized into five weight classes (Bunea 1987): extra light, 0 to 0.01lbs/ft, light 0.01 to 20 lbs/ft, medium 20 to 60 lbs/ft, heavy, 60 to 120 lbs/ft, and extra heavy, >120 lbs/ft. The structural steel unit rate productivity table in the BIM software used for the study is categorized according to the unit weight range (lbs/ft) and function, such as beam, column, and brace of the steel members. However, the unit rate productivity of structural steel in the RichardsonTM's cost database is categorized by the size and function of steel members. In order to match the format of the standard steel unit rate productivity table (SSURT) described in the BIM application used for this study, the research effort transformed the format of the unit rate productivity data obtained from RichardsonTM to the format that is consistent with the software application. Through this conversion, the research effort obtained an aggregated unit rate productivity table illustrated in Table 3-2.

Table 3- 2. Aggregated Unit Rate Productivity Table

Unit Rate (Workhours/Ton)	Component Type	Activity	Productivity Factor	Weight Range	Function
18.846	STEEL_ASSEMBLY	Erect	1	Light	Beam
13.672	STEEL_ASSEMBLY	Erect	1	Medium	Beam
11.242	STEEL_ASSEMBLY	Erect	1	Heavy	Beam
8.499	STEEL_ASSEMBLY	Erect	1	Extra Heavy	Beam
30.292	STEEL_ASSEMBLY	Erect	1	Light	Bracing and Miscellaneous
31.079	STEEL_ASSEMBLY	Erect	1	Medium	Bracing And Miscellaneous
30.383	STEEL_ASSEMBLY	Erect	1	Heavy	Bracing And Miscellaneous
30.691	STEEL_ASSEMBLY	Erect	1	Extra Heavy	Bracing And Miscellaneous
25.579	STEEL_ASSEMBLY	Erect	1	Light	Column
16.26	STEEL_ASSEMBLY	Erect	1	Medium	Column
10.851	STEEL_ASSEMBLY	Erect	1	Heavy	Column
6.159	STEEL_ASSEMBLY	Erect	1	Extra Heavy	Column

Selection of Productivity vs. Temperature and Humidity Model

This dissertation research is built upon the existing knowledge about the relationship between labor productivity versus climate conditions. In the literature review section, the research effort examined different models that depict the relationship between climate conditions and labor productivity. However for this study, the research effort selected a model that suits both cold and hot environments, and covers a wide range of temperature conditions. Among the four models, Grimm and Wanger's (1974) model was developed based on the productivity data collected at temperatures from 40 to 100 °F with relatively humidity of 20 to 100%; Thomas and Yiakoumis' (1987) model has the similar issue with Grimm and Wanger's that the reliability of the model is limited by the range of temperature from 12 to 82 °F; and NECA's model only focuses on a single activity in electrical trades, where the intensity of the work between electrical installation and structural steel erection may differ. Finally, the research effort decided to use

Koehn and Brown's (1985) model to predict labor productivity given a temperature and humidity, since the model was developed based on a larger sample size and considered multiple trades, including the steel trades.

Selection of Project Locations

One of the objectives of this research is to use the developed framework to test how different temperature and humidity scenarios could impact the model project's schedule performance and required man hours. Four cities were selected, including Lexington, Kentucky, Houston, Texas, Newark, New Jersey, and Long Beach, California. Considering the scope of this study described earlier, the following criteria were considered when selecting the four cities:

- 1) Temperature and humidity conditions among the four cities are distinctly different;
- 2) The selected cities are not located in the regions where construction activities are suspended during winter seasons.
- 3) The selected cities are not located in the regions that have a relatively long rainy reason.

The purpose of taking above criteria into consideration was to control the effect of extreme weather conditions on the project's schedule. It aimed to eliminate the "noise" effect that would otherwise be introduced into the data.

Historical Weather Data

To determine the temperature and humidity effect on a project, weather data regarding temperature and humidity were collected. The project was assumed to be situated in Lexington, Kentucky, Houston, Texas, Newark, New Jersey, and Long Beach, California. Climatic conditions may fluctuate from year to year. To capture as many weather scenarios as possible,

the research effort collected the last 50 years' historical weather data from 1961 to 2010 for each of these selected cities. The historical weather data were obtained from the Weather Underground (2013). Weather Underground is a commercial weather service provider, founded in 1995, based in Ann Arbor, Michigan. Weather Undergrounds (WU) currently holds global historical weather data from 1948 up to today. Weather data provided by WU are collected in hourly intervals for most of the years, and some recent years' data are collected with a higher resolution of 15-minute intervals. Detailed information includes temperature, dew point, relative humidity, sea level pressure, visibility, wind direction, wind speed, gust speed, and precipitation. The weather data provided by WU in the U.S. is gathered from over 42,000 weather stations across the countries. These weather stations include over 2,000 Automated Surface Observation System stations located at major airports maintained by Federal Aviation Ministration, over 16,000 Personal Weather Stations (PWS) within WU's network subjected to strict quality control, and over 26,000 weather stations that are part of the Meteorological Assimilation Data Ingest Systems (MADIS) under the administration of National Oceanic and Atmospheric administration (NOAA). Though it is not a governmental agency, WU provides reliable data because of the authoritative data sources. Another commonly cited source that archives historical weather data is the National Climate Data Center (NCDC) under the administration of NOAA. The research effort preferred Weather Underground to NCDC because the historical weather data archived by WU are in a comma delimited format that is supported by many programs. Conversely, some of the older data sets archived by NCDC are scanned copies which would have compromised the efficient data transfer.

A challenge of using Weather Underground data is that one query of weather data for a location can only be made for a specific date instead of a range of dates. Since this dissertation

research required 50 years of historical daily weather data from 4 cities, manually downloading and processing the data would have been cumbersome. In this regard, an automated process was needed to avoid human errors occurring during data retrieval and reentry. To solve this problem, the research effort developed an interface for the download and import of the weather data into the BIM model. This interface (Figure 3- 4) is developed in an MS Excel spreadsheet with Visual Basic for Application (VBA). The VBA code for the interface is listed in the Appendix I. Through this interface, multiple years of historical weather data could be queried, downloaded, and saved as text files automatically. The right side of the interface is used for importing the downloaded weather data in txt files into excel spreadsheets. The readers should note that the download interface is developed in MS Office 2007, and as such compatibility issues may occur if this program is run under MS Office 2010 or later versions.

Interface for Weather Data Download and Import

Download Weather Data

From: Month: January, Date: 1, Year: 2000

To: Month: December, Date: 31, Year: 2000

Location (City): Lexington

Download & Save

Import Weather Data

Directory: False ...

Import

Notes:

This interface is used to download the weather from Weather Underground website.
Url= <http://www.wunderground.com/history/>
The daily weather data was saved in txt files and archived in individual folders by year
The right column of this interface was designed to import daily weather data into excel
Each year's weather data will be saved on each worksheet

Figure 3- 4. Weather Data Download and Import Interface

For this dissertation research, only temperature and humidity data within the regular working hours was investigated. On the model project, the steel craft workers followed a 4×10 working hour schedule, working from 7:00 am to 6:00 pm with a one hour lunch break from Mondays to Thursdays. Temperature data beyond that range were filtered out. Temperature in a day can vary with time. Table 3-3 shows the historical weather data on March 4th, 2009 in Lexington, KY , with temperature ranging from 26.1 °F in the morning to 50 °F in the afternoon.

Table 3- 3. Historical Weather Data on Mar. 4th 2009 in Lexington

Date	Time	Temp. (°F)	Dew Pot: (°F)	R.H.	Sea Level Pressur e (in)	Visibility (mile)	Wd Dir:	Wd Speed (mph)	Gust Speed (mph)	Precip (in)	Events	Conditions
3/4/09	6:54 AM	26.1	6.1	43	30.42	10	SE	8.1	-	N/A		Overcast
	7:54 AM	27	6.1	41	30.42	10	SE	6.9	-	N/A		Mostly Cloudy
	8:54 AM	28	7	41	30.44	10	SSE	5.8	-	N/A		Scattered Clouds
	9:54 AM	35.1	9	34	30.42	10	SSW	5.8	-	N/A		Clear
	10:54 AM	39	10	30	30.41	10	SW	6.9	-	N/A		Clear
	11:54 AM	41	10	28	30.4	10	SW	4.6	-	N/A		Clear
	12:54 PM	45	10	24	30.37	10	Variable	4.6	-	N/A		Clear
	1:54 PM	46.9	7	20	30.34	10	WSW	9.2	-	N/A		Clear
	2:54 PM	48	6.1	18	30.31	10	SSW	8.1	-	N/A		Clear
	3:54 PM	50	9	19	30.29	10	Variable	5.8	-	N/A		Clear
	4:54 PM	50	9	19	30.29	10	SSW	9.2	-	N/A		Clear
	5:54 PM	48	10.9	22	30.29	10	SSW	5.8	-	N/A		Clear

Because of the fluctuating temperatures throughout a day, the productivity factor corresponding to each time point where weather data was collected was computed with reference to the productivity factor relative to temperature and humidity listed in Table 3- 1. Then the average productivity factor during the 10 hours is considered as the productivity factor for that specific day. A daily average productivity factor was calculated by utilizing the following Equation 3- 4:

Equation 3- 4

$$F_d = \frac{\sum_i^j \frac{F_{ti} + F_{ti+1}}{2} (t_{i+1} - t_i)}{t_j - t_i}$$

Where, F_d = the average productivity factor during the daytime; F_{ti} = the calculated productivity factor at the i^{th} time point t_i ; F_{ti+1} = the calculated productivity factor at the $(i+1)^{\text{th}}$ time point t_{i+1} .

In that the process of computing daily productivity factor involves large amount of repetitive data processing, the research effort developed a number of macros to automate the computation process. The macro codes are listed in Appendix II.

Baseline Schedule

Develop Work Packages

Work package is a basic unit for site superintendents to organize daily site activities at the crew level. A work package represents the volume of a crew's work in a week. Depending on the size of a crew, the man hours of a work package can vary from 400 to 1200 (CII 2012). The next step of this study is to develop work packages. The practice of work packaging enables construction management to breakdown a complex project into manageable units. Work packages are the key for superintendents to estimate the materials, and labor costs precisely and make sure that the required resources are available at the right time. A large scaled project can have hundreds or thousands of work packages. Therefore, a systematic naming convention for work packages is instrumental. A self-explanatory name assigned to each work package and organized in a proper order enables model viewers to identify specific work packages in a quick manner. Therefore, this research effort used a combination of floor numbers and predefined sequence numbers as a prefix for a work package. Usually before the construction stage, a steel

structure is broken down into a number of sequences and a sequence number is designated to a group of steel components. Once the sequence is established, sequence numbers are referred among steel fabricators and contractors for scheduling materials fabrication and delivery. When the research effort developed work packages, a sequence was divided into several work packages depending on the total work hours required. Most of the time, a sequence is broken down into multiple erection and detailing packages. For sequences with smaller amounts of steel members, a work package can include both erection and detailing activities.

Create Base Construction Schedule

After work packages were created, a baseline schedule was developed. Since this model project is an already completed project, the creation of the baseline schedule followed the precedence of the actual construction tasks taken place on the actual project. The baseline schedule described herein did not consider the temperature and humidity effect yet. The unit rate productivity obtained from the Richardson cost data was collected from the activities that were undertaken under the conditions with optimal temperatures, adequate skilled craft workers, decent material supply, easy site access, and proper supervision, which as a whole can be considered as optimal baseline productivity. The studied healthcare facility project was executed with the assistance of BIM technology. A thorough constructability coordination was enforced on the whole project. Clash detection and trade coordination were performed on the BIM model before the actual construction activities took place. Thus, construction rework was greatly reduced. In this dissertation research, rework was not counted in the creation of the baseline schedule. Work packages were treated as basic schedule task units, since work packages are also the work units assigned to work crews according to jobsite practices. Through the process of virtual construction model processing described in the previous section, the information of work

hours required for the installation of each steel component was populated in the model. Therefore, each work package included the information of total work hours required for installation. By referring to the man power log recorded by the contractor, the duration for each work package was computed. Cross-referencing the precedence between the activities on the real project, the baseline construction schedule at a crew level with work packages as task units was developed.

Algorithm of Schedule Simulation

This section describes the algorithm of schedule simulation considering temperature and humidity effects. The research effort developed an interface for schedule simulation within the Excel spreadsheet with VBA scripts to accomplish the automated process (Figure 3- 5). The code of the program is attached in the Appendix III. One of the eminent advantages of BIM is its data interoperability; the work package report can be exported directly from the model database into the excel spreadsheet, which eliminates manual data reentry. The interested information for the schedule simulation is the work package items and the work hours associated with each work package. The schedule simulation interface was developed based on early start and early finish. The column of "Predecessors" depicts the precedence between the schedule tasks. For example, as shown in Figure 3- 5, Task 6-7thLv- SEQ10-WorkPack2-Erection's predecessor is listed as "3FS+0". In this case, "3" describes the Task ID, "FS" describes the finish-to-start relationship, and "0" denotes the lag between a task's finish date of and its successor's start date. In this example, "3FS+0" can be interpreted as the described task's predecessor is 6-7thLv-SEQ10-WorkPack1-Erection, and the task starts right after the predecessor finishes. Likewise, SS denotes start-to-start relationship, SF denotes start-to-finish, and FF denotes finish-to-finish relationship. Figure 3- 6. describes the flow chart of the schedule simulation algorithm. For the

process of simulation, Fridays, Saturdays, Sundays, and national holidays are assumed as non-work days. Once a start date is picked as the simulation start date, test for working or non-working day test is performed. If the test is false, the next day is picked and the working/non-working day test is repeated. This process is repeated until the test becomes true. If it is a working day, the task to be executed, work hours for the task, productivity factors, number of workers, and work hours in the that day are identified, so that the quantity installed during that day can be computed. Then another logic test, if the task is done, is performed. If the task is not finished, the next day is picked. The loop repeats until the task is done, and the required duration is recorded. Possibly, one task could be completed is before the end of day. In this case, the rest of day could be used to perform the next task.

Through the schedule simulation interface, the user can specify a period of time during which a project start date can be picked, then click the "Run" button (Figure 3- 5). The simulated start and finish dates, and durations required to build the model project can be automatically computed and stored in an "Output" Excel spreadsheet.



University of Colorado Boulder

Schedule Simulation Interface

Run

Simulation Time Frame

From	Month	Date	Year	To	Month	Date	Year
	January	1	1961		July	31	2010

TaskID	TaskName	Location	ActivityType	ActualFinish	Predecessors	SimulatedDuration	SimulatedStart	SimulatedFinish	SimulatedWorkhour
1	1-3rdLv-SEQ63-WorkPack1-Erection&Detailing	SEQ63	E&D			2.7	7/1/2050	07/06/2050	106.1
2	2-3rdLv-SEQ66-WorkPack1-Erection&Detailing	SEQ66	E&D		1SS+4	2.6	7/7/2050	07/12/2050	76.8
3	6-7thLv-SEQ10-WorkPack1-Erection	SEQ10	Erection		2SS+2	5.4	7/12/2050	07/20/2050	808.4
4	6-7thLv-SEQ10-WorkPack2-Erection	SEQ10	Erection		3FS+0,1FF+0,2FF+0	5.9	7/20/2050	08/01/2050	882.1
5	6-7thLv-SEQ10-WorkPack3-Detailing	SEQ10	Detailing		4SS+3	7.2	7/26/2050	08/08/2050	578.8
6	6-7thLv-SEQ11-WorkPack1-Erection	SEQ11	Erection		5SS+1	5.6	7/27/2050	08/04/2050	833.5
7	6-7thLv-SEQ11-WorkPack2-Erection	SEQ11	Erection		6FS+0	3.7	8/4/2050	08/11/2050	559.9
8	6-7thLv-SEQ11-WorkPack3-Detailing	SEQ11	Detailing		6SS+4,7FF+0	9.4	8/3/2050	08/18/2050	469.7
9	6-7thLv-SEQ12-WorkPack1-Erection	SEQ12	Erection		6SS+6	5.7	8/8/2050	08/16/2050	848.3
10	6-7thLv-SEQ12-WorkPack2-Erection	SEQ12	Erection		9FS+0	4.1	8/16/2050	08/23/2050	608.7
11	6-7thLv-SEQ12-WorkPack3-Detailing	SEQ12	Detailing		10FS+0	4.9	8/23/2050	08/31/2050	488.8
12	8-9thLv-SEQ13-WorkPack1-Erection	SEQ13	Erection		9SS+9	5.3	8/23/2050	08/31/2050	848.3
13	8-9thLv-SEQ13-WorkPack2-Erection	SEQ13	Erection		12FS+0	5.2	8/31/2050	09/08/2050	833.6
14	8-9thLv-SEQ13-WorkPack3-Detailing	SEQ13	Detailing		13FS+1,11FS+0	9.4	9/12/2050	09/27/2050	561.0
15	8-9thLv-SEQ14-WorkPack1-Erection	SEQ14	Erection		13FS+0	5.7	9/8/2050	09/20/2050	848.4
16	8-9thLv-SEQ14-WorkPack2-Erection	SEQ14	Erection		15FS+0	3.8	9/20/2050	09/26/2050	563.1
17	8-9thLv-SEQ14-WorkPack3-Detailing	SEQ14	Detailing		16FS+0	6.7	9/26/2050	10/06/2050	467.3
18	8-9thLv-SEQ15-WorkPack1-Erection	SEQ15	Erection		15SS+6	5.7	9/20/2050	09/28/2050	848.4
19	8-9thLv-SEQ15-WorkPack2-Erection	SEQ15	Erection		18FS+0	3.8	9/28/2050	10/05/2050	564.3
20	8-9thLv-SEQ15-WorkPack3-Detailing	SEQ15	Detailing		18FS-1,14FF+0,17FF+0,19FF+0	11.7	9/27/2050	10/17/2050	468.0
21	10-11thLv-SEQ16-WorkPack1-Erection	SEQ16	Erection		18SS+12	2.9	10/11/2050	10/13/2050	836.5
22	10-11thLv-SEQ16-WorkPack2-Erection	SEQ16	Erection		21FS+0	2.8	10/13/2050	10/19/2050	821.8
23	10-11thLv-SEQ16-WorkPack3-Detailing	SEQ16	Detailing		22FS+0	11.0	10/19/2050	11/08/2050	549.9
24	10-11thLv-SEQ18-WorkPack1-Erection	SEQ18	Erection		21SS+5	4.6	10/19/2050	10/26/2050	836.5
25	10-11thLv-SEQ18-WorkPack2-Erection	SEQ18	Erection		24FS+0	2.8	10/26/2050	11/01/2050	508.0
26	10-11thLv-SEQ18-WorkPack3-Detailing	SEQ18	Detailing		25FS+0	7.4	11/1/2050	11/14/2050	442.5
27	10-11thLv-SEQ19-WorkPack1-Erection	SEQ19	Erection		24SS+5	5.5	10/27/2050	11/07/2050	829.2
28	10-11thLv-SEQ19-WorkPack2-Erection	SEQ19	Erection		27FS+0	3.8	11/7/2050	11/14/2050	568.3
29	10-11thLv-SEQ19-WorkPack3-Detailing	SEQ19	Detailing		28FS+0,23FF+0,26FF+0	9.3	11/14/2050	11/29/2050	464.2

Figure 3- 5. Schedule Simulation Interface

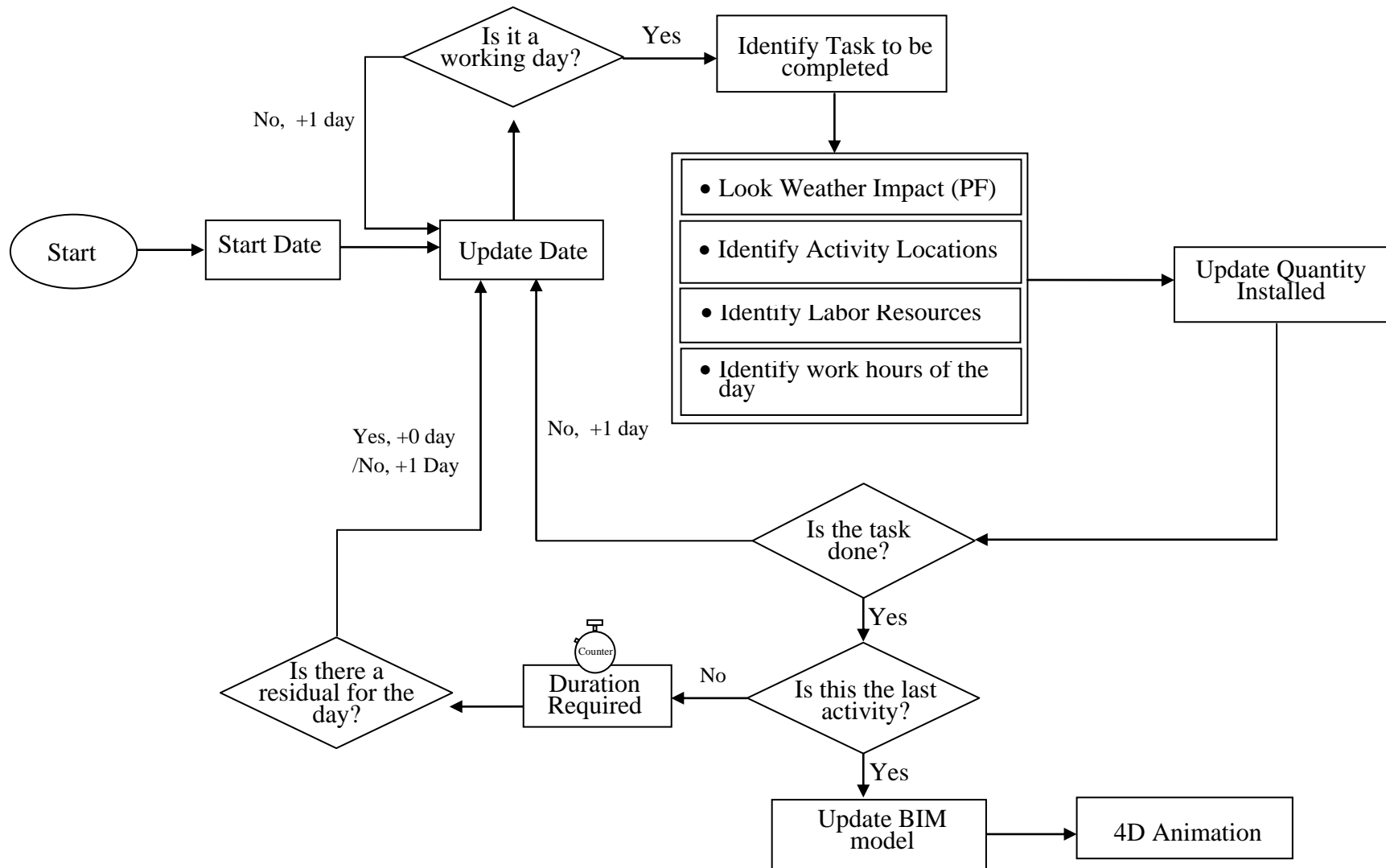


Figure 3- 6. Flow Chart of the Algorithm for Schedule Simulation

4D Schedule Animation

4D schedule animation is usually used to visually present how a building is built and also to visualize a project's construction status with respect to a timeline. 4D schedule animation is achieved through linking the model objects with project schedule. For this research project, in order to link the schedule with 3D models automatically, the names of the work package created in the model match the task names in the schedule. To visually compare the schedule performance under two different scenarios, two 4D schedule animations can be played in parallel.

Model Validation

The model validation process is to test if the built model behaves properly as it is intended. The research effort used the developed schedule simulation interface and set the simulation start date the same as the actual project start date, May 18, 2009. Lexington's historical temperature and humidity data of the years 2009 and 2010 were used to derive productivity factors that act upon labor productivity. The simulation process followed a working schedule of 4×10 hours/week. As mentioned, this research did not take precipitation into consideration. However, the actual project suffered from a number of rainy days and used some weekends and overtime shifts to make up the loss of working days due to sporadic unworkable days. Therefore, precipitation would not constitute a major threat to the project delay. The simulated start and finish dates for each work package, and the total work hours required to build the project were generated. As shown in Table 3- 4, the simulated project finish date considering the temperature and humidity effect is November 18, 2010 as opposed to the actual completion date, November 23, 2010. The difference in total work hours required to build the project between simulated and actual results amounts to 518 work hours, which is within 1% of error.

Table 3- 4. Summary of Developed Framework Validation

	Simulated	Actual
Project Start Date	5/18/2009	5/18/2009
Project Finish Date	11/18/2010	11/23/2010
Total Work Hours Required	55,465	54,947

Figure 3- 7. shows the actual and simulated man-power loading over the whole duration of structural steel erection. Though variation presents , the overall trends show a large degree of consistency because some amount of rework and overtime presented in the actual project.

The process of validation provides the confidence that the aggregated unit rate productivity obtained from Richardson's cost data, selected productivity model, and the developed simulate interface are reliable enough to be used and generate meaningful knowledge against temperature and humidity impacts on a project.

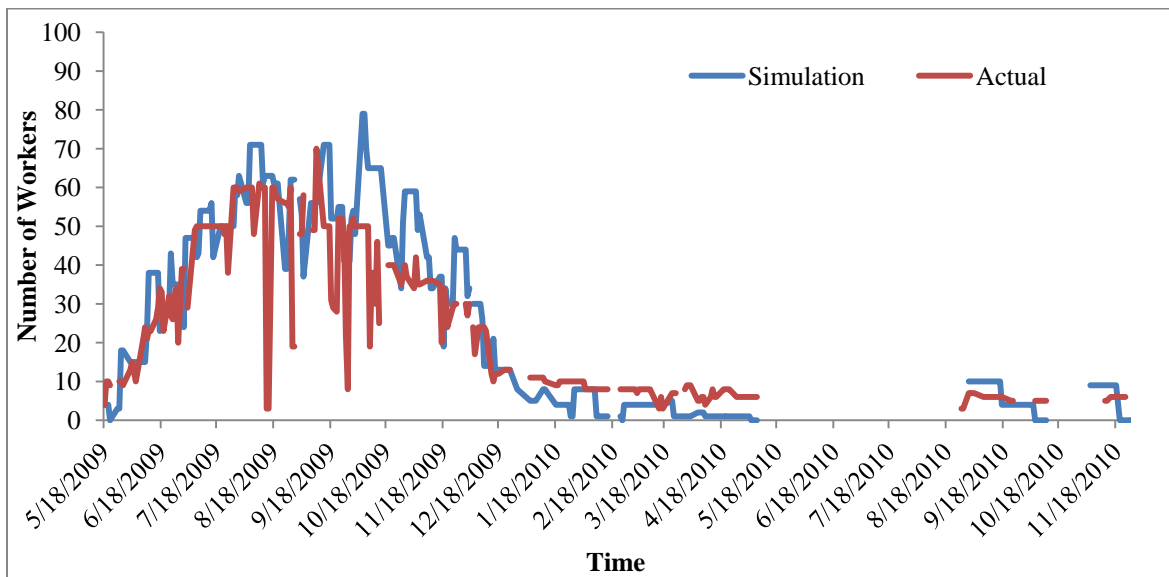


Figure 3- 7. Man Power Loading of Simulation vs. Actual Record

Schemas

One of the objectives of this research is to use this developed frame work to generalize strategies with regard to temperature and humidity effects. To accomplish this goal, the research effort proposed the following schemas to perform the simulations and statistical analyses on the generated the simulation results.

The research effort picked four specific dates in a year as the project starting dates for the schedule simulation. The four dates are the 1st day of the quarters of the year, i.e. January 1st, April 1st, July 1st, and October 1st, which allows the project to have an equal probability of exposure to temperature and humidity changes due to seasons. 50 years of historical data of the four selected cities were downloaded, and the productivity factor for each day of the last 50 years was calculated. Through the developed schedule simulation interface, the research effort obtained the results of project duration and total work hours required to build the project with respect to each project starting date and location.

With generated simulation data, the research effort performed a series of statistical analyses. Among the generated simulation data, interested dependent variables included total work hours and project durations required to build the project. In this study, there are two factors involved: project start date and project location, which consists of a typical 4×4 two-way analysis of variance (ANOVA). Three hypotheses were tested in this study. The null hypotheses are described as follows:

H1₀: Starting the project on different dates would not change the project duration and work hours required to build the project;

H2₀: Situating the project at different locations would not change the project duration and work hours required to build the project; and

H3₀ : The project location and start date would not interactively effect the project duration and work hours required to build the model project.

RESULTS OF STATISTICAL ANALYSES

Descriptive Statistics

Table 3-5 shows the descriptive statistics about the generated simulation data on total work hours and project durations required to build the model project and the deviation from baseline in percentage, considering the selected project locations and start dates. The deviation from the baseline can be interpreted as the effect of temperature and humidity on the model project. The sample size for each block is 196. As shown in Table 3- 5, the medians and means do not deviate from each other very much.

Table 3- 5. Mean and Median of the Total Work Hours and Project Duration Required with Respect to Each Project Location and Start Date

Location		Work Hours				Project Duration			
		Jan-1	Apr-1	Jul-1	Oct-1	Jan-1	Apr-1	Jul-1	Oct-1
Houston	Mean	56,419 (3.8%)	58,017 (6.8%)	56,364 (3.7%)	55,354 (1.9%)	552 (3.0%)	556 (3.7%)	555 (3.6%)	557 (3.8%)
	Median	56,340 (3.7%)	57,990 (6.7%)	56,325 (3.7%)	55,297 (1.8%)	552 (3.0%)	556 (3.7%)	556 (3.7%)	556 (3.7%)
Lexington	Mean	56,211 (3.4%)	55,654 (2.4%)	56,784 (4.5%)	58,204 (7.1%)	550 (2.7%)	550 (2.7%)	556 (3.7%)	560 (4.5%)
	Median	56,235 (3.5%)	55,632 (2.4%)	56,645 (4.2%)	57,914 (6.6%)	550 (2.6%)	553 (3.2%)	555 (3.5%)	560 (4.5%)
Long Beach	Mean	54,634 (0.5%)	54,964 (1.2%)	54,864 (1.0%)	54,682 (0.6%)	545 (1.8%)	545 (1.8%)	552 (2.9%)	549 (2.5%)
	Median	54,602 (1.0%)	54,891 (0.9%)	54,804 (0.6%)	54,677 (1.9%)	546 (1.7%)	545 (3.0%)	552 (2.4%)	549 (1.0%)
Newark	Mean	56,064 (3.2%)	55,563 (2.3%)	56,313 (3.6%)	57,708 (6.2%)	549 (2.5%)	549 (2.5%)	555 (3.6%)	558 (4.1%)
	Median	56,082 (3.2%)	55,462 (2.1%)	56,082 (3.2%)	57,719 (6.2%)	549 (2.4%)	552 (3.0%)	555 (3.5%)	557 (3.9%)

Note:

The Sample size for each block is 196.

The baseline work hours is 54,337 and project duration is 536 calendar days

() shows the deviation from the baseline work hours and project duration in percentage.

Test for Normality

To determine whether a parametric method is appropriate for the above described statistical tests, the research effort conducted a normality test to see if the samples of the interested variables are normally distributed. There are different methods available to check the normality of the sample distribution, including graphical and numerical methods. The research effort finally adopted one of the graphical methods, Q-Q plot, to check the data distribution against the theoretical normal distribution. The straight line in a Normal Q-Q plot represents the theoretical normal distribution. If the sample data can be considered normal, the plotted data points should generally fall along the line. . and Figure 3- 9. respectively illustrate the Normal Q-Q plots of generated simulation data on total work hours and project durations required to build the model project with respect to four cities and project start dates. A number of plots of total work hours required in . significantly deviates from the straight line, while the Q-Q plots of project duration in Figure 3- 9. shows a better approximation to the normal distribution. For this case, non-parametric methods seem more appropriate for this study since non-parametric methods do not need the assumption of normal distribution of the data. However, the statistics of parametric methods are easier to interpret. The research effort decided to report the results of both parametric and non-parametric statistical tests performed on the data. In addition, using both methods also serves the purpose of comparing the difference of results between the two methods.

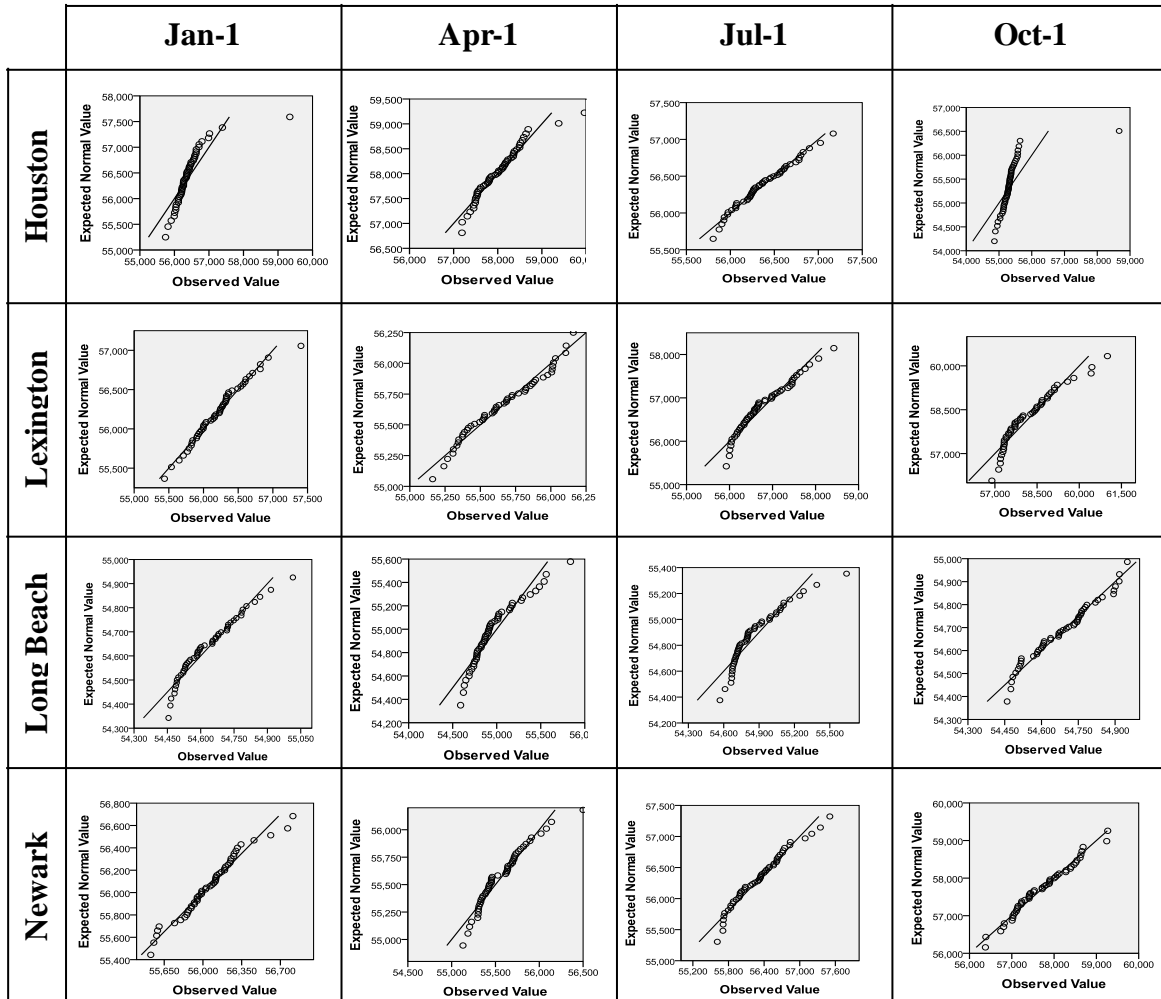


Figure 3- 8. Normal Q-Q Plots of Work Hours Required by Project Start Date and Location

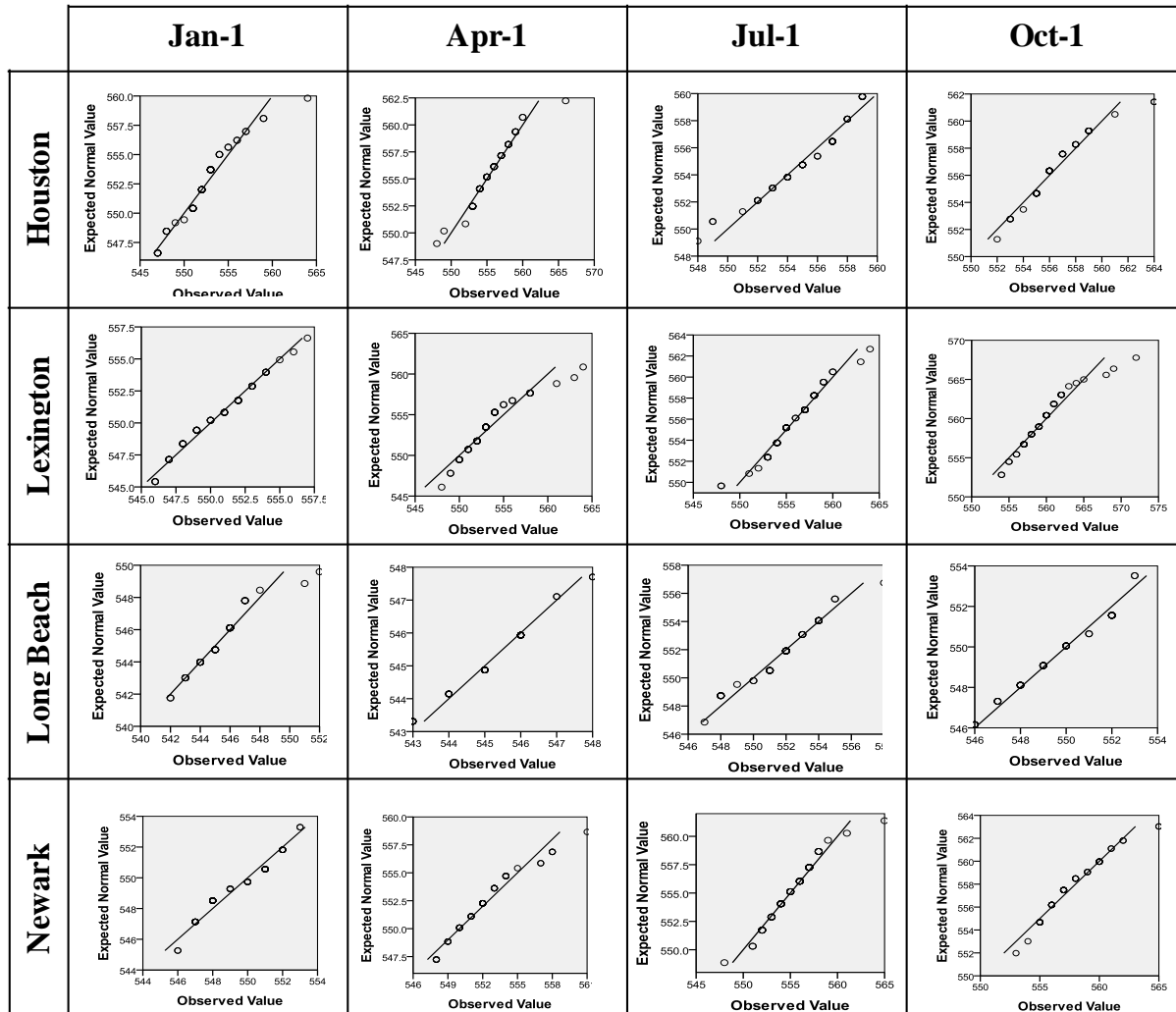


Figure 3- 9. Normal Q-Q Plots of Project Duration by Project Start Date and Location

Results of 2-Way ANOVA

Table 3- 6 shows the summary of parametric 2-way ANOVA of the total work hours and project duration. The results show that, in terms of total work hours and project durations, the population means of the factor, project location, are statistically significantly different at the 99% confidence level; and that the population means of the factor, project start date, are statistically significantly different at the 99% confidence level. The results also show that there is interaction

between project location and start date, and the results are statistically significant at 99% confidence level.

Table 3- 6. Summary of Parametric 2-Way ANOVA of Total Work Hours and Project Duration

Source	Work Hours					Project Duration				
	Sum of Square	d.f.	Mean Square	F	Sig.	Sum of Square	d.f.	Mean Square	F	Sig.
Location	475714820.3	3	158571606.8	746.7	.000	6644.5	3	2214.8	309.7	.000
Start Date	44225292.2	3	14741764.1	69.4	.000	5090.6	3	1696.9	237.2	.000
Location * Start Date	442459960.7	9	49162217.9	231.5	.000	1298.6	9	144.3	20.2	.000
Error	165431294.1	779	212363.7			5572.0	779	7.2		
Total	1126200776.6	794				18589.4	794			

Table 3- 7 presents the summary of non-parametric 2-way ANOVA of total work hours and project durations. Unlike parametric ANOVA, non-parametric test is not able to test the interactions between two factors. In this case, two sets of tests were performed. One was to fix the project location; the research effort studied one project location at a time and used independent-samples median test to test the equality of the medians of the populations for the required total work hours and project durations across categories of project start dates. The other was to fix the project start date; the research effort studied one project start date at a time and tested the medians of the population for the required work hours and project durations across categories of project locations. The results are described in Table 3- 7. For each city, there is a significant difference among the population medians of the total work hours and project duration for at least two start dates. Likewise for each project start date, there is a significant difference among the population medians of the total work hours and project durations for at least two cities.

Table 3- 7. Summary of Non-parametric 2-Way ANOVA of Total Work Hours and Project Duration

Null Hypothesis	Work Hours				Project Duration			
	Grand Median(N)	Test Statistics	d.f.	Sig.	Grand Median(N)	Test Statistics	d.f.	Sig.
The medians of the populations for Houston are the same across categories of project start date	56,335.4(196)	94.3	3	.000	555(196)	34.3	3	.000
The medians of populations for Lexington are the same across categories of project start date	56,360.4(196)	119.6	3	.000	554(196)	101.2	3	.000
The medians of populations for Long Beach are the same across categories of project start date	54,746.1(196)	45.7	3	.000	547(196)	141.1	3	.000
The medians of populations for Newark are the same across categories of project start date	56,143.6(196)	100.0	3	.000	553(196)	119.6	3	.000
The medians of the populations for the start date of Jan-1 are the same across categories of project location	56,048.6(196)	76.7	3	.000	549(196)	61.9	3	.000
The medians of the populations for the start date of Apr-1 are the same across categories of project location	55,614.7(196)	94.3	3	.000	552(196)	93.8	3	.000
The medians of the populations for the start date of Jul-1 are the same across categories of project location	56,243.8(196)	72.1	3	.000	554(196)	50.7	3	.000
The medians of the populations for the start date of Oct-1 are the same across categories of project location	56,381.2(196)	188.2	3	.000	556(196)	83.1	3	.000

Note: N denotes the sample size

Multiple Pairwise Comparisons

ANOVA can only show that there is a statistically significant difference at least between two groups among all of the groups. Figure 3- 10. describes the means of work hours required to build the model project and the difference from baseline by project location across four project start dates. Likewise, Figure 3- 11. describes the means of work hours required to build the model project and the difference from baseline by project start date across four project locations. Since project durations are highly correlated with work hours, the charts depicting project durations are not presented in this paper. From the charts alone, mean differences were observed.

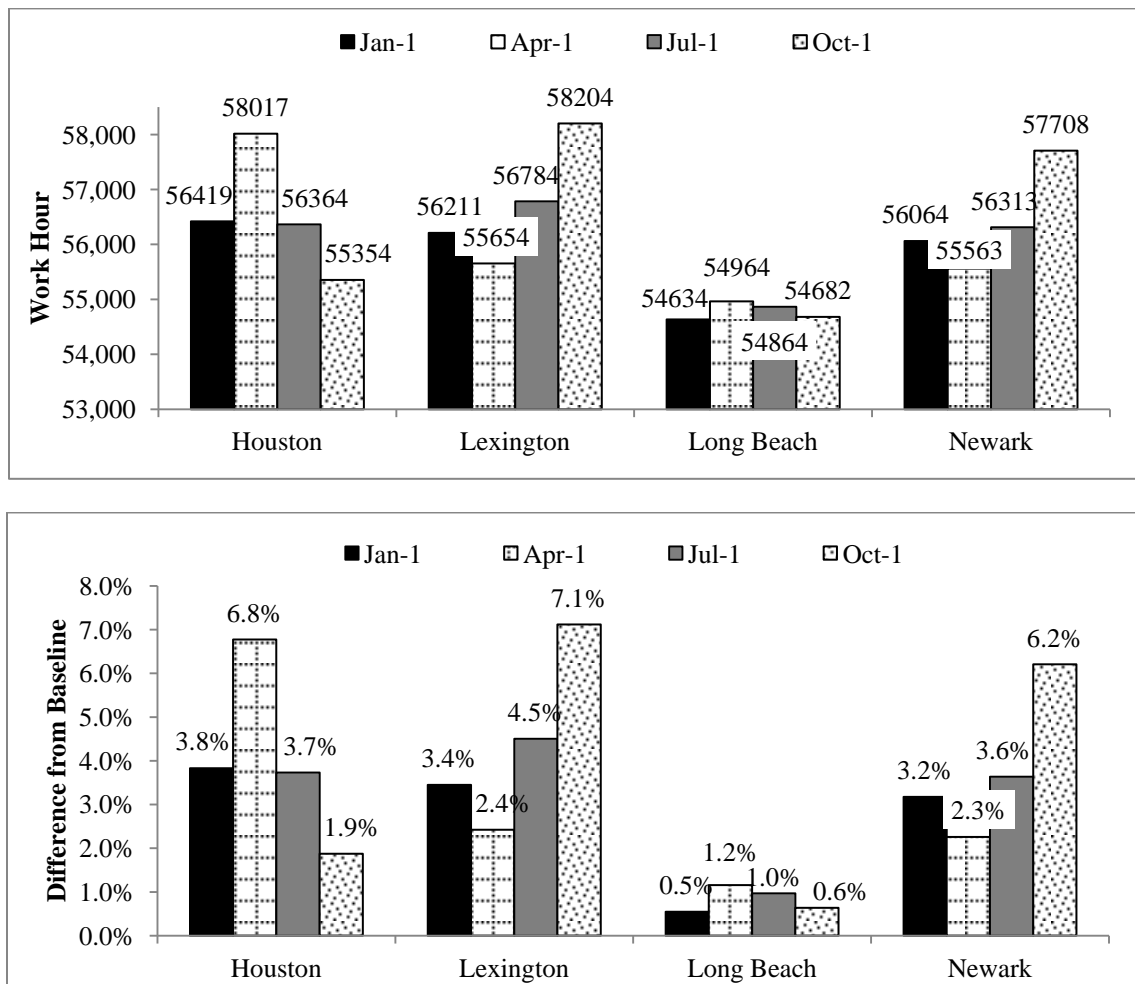


Figure 3- 10. Bar Chart for Mean of Work Hours Required and Difference from Baseline in Percentage by Project Location Across Four Project Start Dates

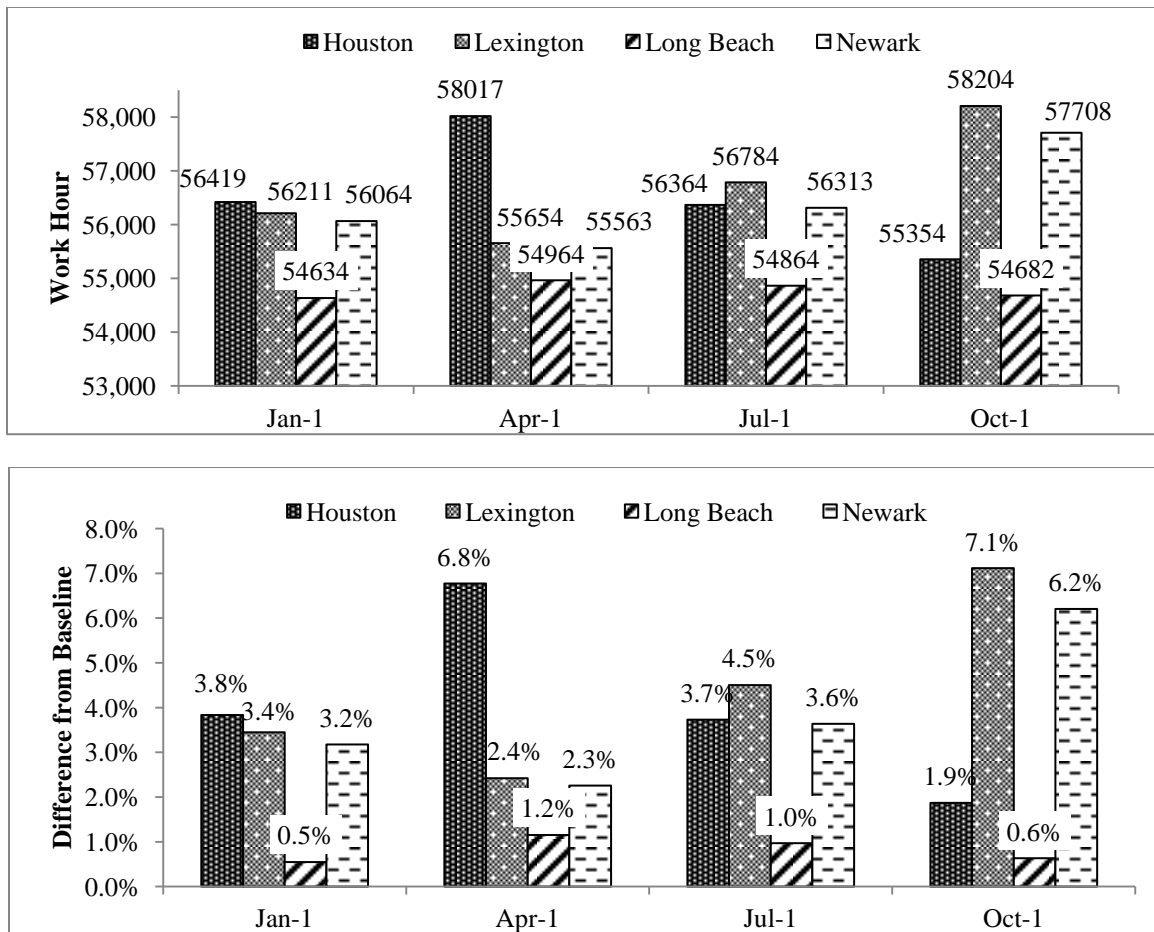


Figure 3- 11. Bar Chart for Mean of Work Hours Required by Project Start Date Across Four Locations

To further investigate where the statistically significant differences lie among the groups, multiple pairwise comparisons were used to detect all possible statistically significant differences among all of the combinations of pairs. For this study, the research effort performed multiple pairwise comparisons using Tukey's HSD both in parametric and non-parametric methods. Two major categories of tests were performed. One is to compare the difference of work hours and project durations between different project start dates for each selected city. The other is to compare the difference of work hours and project durations between different project locations for each selected project start date.

Table 3- 8 and Table 3-9 show the results of the multiple pairwise comparisons. By and large, both parametric and non-parametric methods show consistent results regarding rejection of the null hypotheses, except in one case where the difference of work hours required between start dates, January 1 and July 1, for Newark, was not detected with the non-parametric method. Though there are a great number of statistically significant differences observed in project duration, the magnitude of the difference is not striking. However among the cities, Houston, Lexington, and Newark, the differences of work hours required between different project start dates can even reach as many as over 2,000 work hours, which represents a significant amount of labor costs. With regard to the total work hours required to build the model project in Long Beach, project start date plays a negligible role since the differences are not remarkable, ranging from 48.1 to 329.9 work hours.

Table 3- 8. Multiple Pairwise Comparisons of Work Hours and Project Duration Required Between Various Project Start Dates by Location (Parametric Method)

		Work Hour [Mean Diff.(Sig)]			Project Duration [Mean Diff.(Sig)]		
		Apr-1	Jul-1	Oct-1	Apr-1	Jul-1	Oct-1
Houston	Jan-1	-1597.9(.000)	55.3(.941)*	1065.4(.000)	-3.3(.000)	-3.0(.000)	-4.3(.000)
	Apr-1		1653.2(.000)	2633.3(.000)		.3(.949)*	-1.0(.302)*
	Jul-1			1010.1(.000)			-1.3(.107)*
Lexington	Jan-1	557.2(.000)	-573.5(.000)	-1993.1(.000)	-3.0(.000)	-5.3(.000)	-9.4(.000)
	Apr-1		-1130.7(.000)	-2550.3(.000)		-2.3(.002)	-6.4(.000)
	Jul-1			-1419.7(.000)			-4.1(.000)
Long Beach	Jan-1	-329.9(.000)	-230.2(.000)	-48.1(.626)*	.3(.856)*	-6.3(.000)	-3.9(.000)
	Apr-1		99.6(.062)*	281.8(.000)		-6.6(.000)	-4.2(.000)
	Jul-1			182.1(.000)			2.5(.000)
Newark	Jan-1	500.8(.000)	-249.7(.034)	-1644.6(.000)	-2.9(.000)	-5.8(.000)	-8.5(.000)
	Apr-1		-750.5(.000)	-2145.4(.000)		-3.0(.000)	-5.6(.000)
	Jul-1			-1394.9(.000)			-2.7(.000)

Note: The difference was derived from the subtraction the values corresponding to row headings by values corresponding to column headings.

* denotes the difference is not statistically significant at 95% confidence level.

Table 3- 9. Multiple Pairwise Comparisons of Work Hours and Project Duration Required Between Various Project Start Dates by Location (Non-parametric Method)

		Work Hour [Rank Diff.(Sig)]			Project Duration [Rank Diff.(Sig)]		
		1-Apr	1-Jul	1-Oct	1-Apr	1-Jul	1-Oct
Houston	Jan-1	-71.6(.000)	.8(1.000)	70.5(.000)	-60.6(.000)	-57.9(.000)	-77.9(.000)
	Apr-1		72.4(.000)	142.1(.000)		2.7(1.000)*	-17.3(.774)*
	Jul-1			69.7(.000)			-20.0(.475)*
Lexington	Jan-1	47.4(.000)	-38.4(.005)	-88.5(.000)	-35.8(.010)	-74.5(.000)	-117.2(.000)
	Apr-1		-85.8(.000)	-135.9(.000)		-38.6(.004)	-81.3(.000)
	Jul-1			-50.1(.000)			-42.7(.001)
Long Beach	Jan-1	-82.4(.000)	-64.6(.000)	-16.7(.874)*	7.4(1.000)*	-104.1(.000)	-70.8(.000)
	Apr-1		17.8(.725)*	65.7(.000)		-111.5(.000)	-78.3(.000)
	Jul-1			65.7(.000)			33.3(.020)
Newark	Jan-1	52.6(.000)	-19.8(.507)*	-83.9(.000)	-42.4(.001)	-87.7(.000)	-120.9(.000)
	Apr-1		-72.3(.000)	-136.5(.000)		-45.3(.000)	-78.4(.000)
	Jul-1			-64.2(.000)			-33.2(.022)

Note: The difference was derived from the subtraction the values corresponding to row headings by values corresponding to column headings.

* denotes the difference is not statistically significant at 95% confidence level.

Table 3- 10 and Table 3- 11 show the results of the multiple pairwise comparisons of work hours and project duration required between different project locations given the same specific project start dates using parametric and non-parametric methods, respectively. Both parametric and non-parametric methods afford similar results with only slight differences. For both work hours and project durations required, non-parametric methods failed to reject the null hypotheses that there is no statistically significant difference between Houston and Lexington when the model project starts on January 1, and that there is no statistically significant difference between Newark and Lexington when the model project starts on October 1. Situating the project to start on the first day of each quarter, the difference in required work hours among the cities shows a broad range, from 50.9 to 3,521.9 work hours.

Table 3- 10. Multiple Pairwise Comparisons of Work Hours and Project Duration Required Between Various Project Locations by Start Date (Parametric Method)

		Work Hour [Mean Diff.(Sig)]			Project Duration [Mean Diff.(Sig)]		
		Lexington	Long Beach	Newark	Lexington	Long Beach	Newark
Jan-1	Houston	208.5(.020)	1785.4(.000)	355.9(.000)	1.9(.002)	6.9(.000)	3.1(.000)
	Lexington		1576.9(.000)	147.4(.167)*		5.0(.000)	1.2(.090)*
	Long Beach			-1429.5(.000)			-3.8(.000)
Apr-1	Houston	2363.6(.000)	3053.4(.000)	2454.6(.000)	2.1(.001)	10.5(.000)	3.4(.000)
	Lexington		689.8(.000)	91.0(.581)*		.8(.000)	1.3(.088)*
	Long Beach			-598.8(.000)			-7.0(.000)
Jul-1	Houston	-420.2(.000)	1499.9(.000)	50.9(.933)*	-.5(.804)*	3.5(.000)	.2(.986)*
	Lexington		1920.1(.000)	471.1(.000)		4.0(.000)	.7(.545)*
	Long Beach			-1449.0(.000)			-3.3(.000)
Oct-1	Houston	-2850.0(.000)	671.9(.000)	-2354.1(.000)	-3.2(.000)	7.3(.000)	-1.2(.138)*
	Lexington		3521.9(.000)	495.9(.001)		10.5(.000)	2.1(.001)
	Long Beach			-3026.1(.000)			-8.5(.000)

Note: The difference was derived from the subtraction the values corresponding to row headings by values corresponding to column headings.

* denotes the difference is not statistically significant at 95% confidence level.

Table 3- 11. Multiple Pairwise Comparisons of Work Hours and Project Duration Required Between Various Project Locations by Start Date (Non-parametric Method)

		Work Hour [Rank Diff.(Sig)]			Project Duration [Rank Diff.(Sig)]		
		Lexington	Long Beach	Newark	Lexington	Long Beach	Newark
Jan-1	Houston	20.5(.443)*	118.0(.000)	39.4(.004)	24.7(.181)*	112.3(.000)	44.5(.001)
	Lexington		97.5(.000)	18.9(.595)*		87.6(.000)	19.8(.493)*
	Long Beach			-78.6(.000)			-67.7(.000)
Apr-1	Houston	71.1(.000)	141.3(.000)	81.6(.000)	33.0(.023)	125.4(.000)	49.7(.000)
	Lexington		70.2(.000)	10.5(1.000)*		92.4(.000)	16.7(.865)*
	Long Beach			-59.8(.000)			-75.7(.000)
Jul-1	Houston	-30.3(.049)	89.4(.000)	4.7(1.000)*	-8.7(1.000)*	69.8(.000)	6.3(1.000)*
	Lexington		119.7(.000)	345.0(.014)		78.5(.000)	15.0(1.000)*
	Long Beach			-84.8(.000)			-63.5(.000)
Oct-1	Houston	-78.6(.000)	50.1(.000)	-64.0(.000)	-46.1(.000)	75.8(.000)	-19.5(.527)*
	Lexington		128.7(.000)	14.6(1.000)*		122.0(.000)	26.6(.119)*
	Long Beach			-114.1(.000)			-95.3(.000)

Note: The difference was derived from the subtraction the values corresponding to row headings by values corresponding to column headings.

* denotes the difference is not statistically significant at 95% confidence level.

IMPLICATIONS OF THE STATISTICAL ANALYSES

The results of the 2-way ANOVA show that the main effect, project start date and location, significantly impacts the work hours and project durations required to build the model project, and that project start date and location interactively influence the total work hours and

project durations. This finding is very intuitive since project location and season jointly contribute to the different weather patterns, consequently affecting craft workers' productivity.

Besides the accuracy of work hour estimate provided by BIM integrated with productivity and productivity factors, another advantage of using BIM to perform the described study is the 4D schedule analysis. Parallel comparison of multiple 4D schedule animation allows construction practitioners to visualize the productivity changes under different project execution scenarios. Figure 3- 12. demonstrates an example of the schedule performance comparison using a 4D schedule analysis when the model project in Lexington, KY is built with two different start dates, April 2, 2007 and October 1, 2007. The figure presents the status of project progress at 5 different time points and the differences are highlighted with red circles.







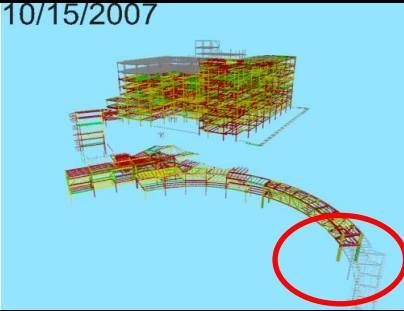
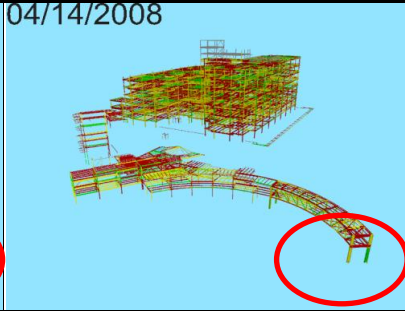


Calendar Days Elapsed	Starts 04/02/2007	Starts 10/01/2007
105 Days	07/16/2007 	01/14/2008 
150 Days	08/30/2007 	02/28/2008 
168 Days	09/17/2007 	03/17/2008 
196 Days	10/15/2007 	04/14/2008 
245 Days	12/03/2007 	06/02/2008 

Figure 3- 12.Comparison of Schedule Performance between Project Start Date 4/2 and 10/1/ 2007 in Lexington, KY

Note: Gray color represents the work at the beginning stage; color represents the work completed.

The procedure of the multiple pairwise comparison has a number of merits to various parties involved in a project, depending on the perspective each party is concerned. Fixing the project location and comparing the work hours required between different project start dates enable contractors to understand the magnitude of work hour differences attributed to the temperature and humidity's impact on labor productivity due to varied project start dates, so that when they bid their projects they can take the difference into consideration, which renders more accurate estimates. Take this particular model project examined in this study as an example. On average, when the project located in Lexington starts its execution on October 1, the total work hours required to build the project increase by 2,550 hours (4.6%) compared to the work hours required when execution starts on April 1. Four-point-six percent is a very significant number to the construction industry in that the average net profit of the construction industry is 6.33% (BizStats 2013). With a lower profit margin, an accurate cost estimate is very essential for a contractor's success (Waddle 2009). From the point of view of owners, if the schedule is not the primary driver over costs, owners can plan to start a project at a optimal timing which could render the lowest project costs. Supposedly all other evaluation criteria are the same, owners also can use the statistical results to select a best location from a list of potential project locations that require the lowest construction costs.

The statistical analysis results can also provide a unique dimension about project portfolio management (PPM) for business owners who conduct business across the country. The objectives of PPM are to maximize the contributions of a collection of projects to the overall financial and operational goals of an organization with various imposed constraints (Rajegopal et al. 2007). Major retailers, such as Walmart, Target, Lowes, and Home Depot, often have buildings built at different locations with similar footprints and designs. It is very likely that

owners could have proposed a few projects that are going to be built at a collection of selected project locations. This framework allows decision makers to minimize the construction costs of the project portfolio by scheduling each project at specific location with optimal project start date. The author readily acknowledge that project costs are just one of the factors being considered during the process of PPM; however, the concept proposed in this study extends an extra dimension to the existing decision making criteria.

CONCLUSIONS AND LIMITATIONS

This research provides a framework of integrating BIM and CPM schedule to simulate the temperature and humidity impact on productivity at a project level. The research effort took a model project as the test model and selected four project locations and their last 50 years of historical weather data to demonstrate the applicability of the framework. The demonstration of the statistical analyses of the simulated results shows how the simulation results can be exploited to generate knowledge for decision making. Since this study took a specific model project and four project locations, the results of the study cannot be directly applied to a different project. Therefore, the external validity of the statistics might be limited. However, the external validity of the developed framework is still preserved. The readers should direct their attention to the framework, because the concept can be generalized to any project.

Based on the statistical analysis of the simulation results, the generalized findings are drawn as follows:

- 1) Temperature and humidity difference due to project geographical location can impact the work hours and project durations required to build a project;

2) Temperature and humidity difference due to seasonal effect can also impact the work hours and project durations required to build a project; and

3) Project location and start date have an interaction in effecting the work hours and project durations required to build a project.

This research will contribute to the overall body of knowledge in the construction industry in several unique ways:

1) Project estimators can use this framework to simulate the temperature and humidity effects on their projects and better estimate their effect at the project level, as such to improve the certainty level of the project estimation.

2) For project decision makers, this research provides a unique venue of helping decision makers to evaluate how project start dates could influence labor productivity, thus influence project durations and costs.

3) This research also adds a dimension to evaluation criteria that a company can use for site selection when considering expanding their business to new geographic locations.

4) Business owners who standardize their project designs and operate business across the country can use this framework to optimize project portfolio's construction costs.

The limitations of the research include the followings:

1) This research is built on an existing productivity model that describes the relationship between productivity factor and temperature and humidity. The validity of this research relies on the validity of the chosen model.

2) Only the steel trade is examined for this project because the BIM application used for this research targets piping and steel trades.

3) This research did not take precipitation (rainfalls or snowfalls) into consideration. To use this framework to perform a simulation in those regions with excessive seasonal perceptions, the user needs to customize the workable day table to exclude some rainy days from the working days.

4) This research used historical weather data to perform the simulation. In order to harness this model as a predictive model, weather data projections obtained from a robust weather generator are needed.

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CHAPTER 4
CONSTRUCTION PRODUCTIVITY IMPACTS OF FORECASTED
GLOBAL WARMING TRENDS UTILIZING AN INTEGRATED
INFORMATION MODELING APPROACH

AUDIENCE: Practitioners and Researchers

ABSTRACT

Forecasted global warming trends are anticipated to increase the average temperature and affect humidity. As a result, changes in indoor and outdoor heat loads and humidity could impair construction labor productivity on a global scale. The objective of this study is to utilize a novel framework to examine the anticipated rise in temperature and humidity change's impact on construction productivity at a project level in terms of work hours required to build a model construction project. This research is established on an existing labor productivity model that quantifies changes in labor efficiency with changes in temperature and humidity. It utilizes a schedule simulation framework that applies building information modeling (BIM) integrated with labor productivity information, and critical path method (CPM) schedule to simulate the global warming effect on a model steel structural erection project. Six international and one domestic cities' climate projection data between the years 2050 to 2099 derived from existing global climate models with different greenhouse gas (GHG) emission scenarios were used as input data for the simulation to quantify the work hours required to build the model project. The 1st day of each quarter of a year was used as the schedule simulation start date. The simulation results of the project's schedule performance considering global warming with various emission scenarios were compared with the project performance under pre-industrial control and current weather scenarios. The findings show that Khartoum, Delhi, Houston, and Brasilia are anticipated to experience productivity losses; Melbourne and Chongqing will be the least impacted; and Moscow is anticipated to have productivity gains depending on the climate model. Finally, the strategies for accommodating global warming's effect on construction labor productivity are discussed. This research effort contributes to the overall body of knowledge by

providing a novel framework of exploring the impact of forecasted global warming trends on a project through an integrated BIM and CPM schedule simulation approach, and the generated knowledge based on the analyses of simulation results can be of interest to construction companies that conduct business in the examined regions.

KEY WORDS: Construction Labor Productivity, Temperature and Humidity, Global Warming, Building Information Modeling (BIM), Steel Trades

INTRODUCTION

Global warming is a prominent issue that has drawn a great deal of attention. Although there are questions surrounding the validity of global warming theories because of the lack of meteorological and oceanic data before the 1800s, the last 250 years of scientific evidence has shown that earth's average surface temperature has increased by approximately 1.4 °F (Committee on America's Climate Choices 2011), and the global average sea level has been rising by 1.7 mm/year over the last 100 years (National Climatic Data Center 2013). Generally speaking, global warming has been accepted as a fact by the public. Global warming could cause the climate change, including temperature increases, climate pattern shifts, and extreme weather events such as, droughts, heavy rain falls, and excessive heat waves (Lu et al. 2007). The climate change due to global warming is anticipated to vary by geographic regions (Solomon et al. 2007). The temperature increases that happened over the last three decades account for two thirds of the change occurred over the last 100 years (Committee on America's Climate Choices 2011). If global warming continues developing with this magnitude, noticeable climate change would appear sooner. The environmental impact due to global warming, to some degree, will eventually affect human activity, including industrial productivity.

Hot working environments have always been a concern for the construction industry. Hot temperatures not only affect construction workers' comfort but also impose a health threat to workers (Kjellstrom et al. 2009). High temperatures coupled with other factors, such as high humidity, direct sun exposure, zero air flow, low liquid intake, heavy workloads, improper clothing, and limited acclimatization are the risk factors for heat related injuries (OHSA 2013). Hot environments affect construction workers' psychological and physiological states. Psychologically, unpleasant working conditions can invoke worker's apathy to work, and physiologically, construction workers can suffer heat stress or stroke (Koehn and Brown 1985). The immediate effects of global warming are broad scales of temperature increases. Coupled with other predicted shifts in weather patterns, it is very likely that prolonged warmer seasons would appear. This implies that construction workers will have more working days under hot environments. As a result, the construction industry will likely expend more efforts in occupational safety to reduce heat related injuries.

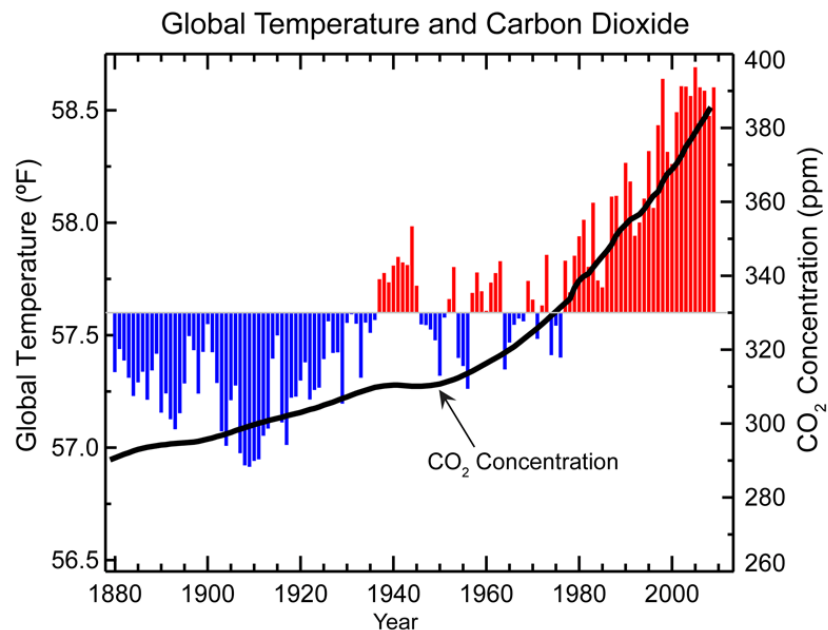
Hot environments not only constitute threats to construction workers' health and safety but also are a cause of productivity losses. Hot weather induces construction worker's loss of enthusiasm for work, restlessness, and irritability (Hancher and Abd-Elkhalek 1998). To protect workers from heat related injuries, the frequency of scheduled breaks and liquid in-takes must increase (OHSA 2013). Therefore, workers' direct work rate decreases as more personal and idle time is introduced. The direct work rate described herein is the ratio of the time attributed to "the act of exerting physical effort directly toward an activity or physically assisting in these activities" to the whole period of time under observation (Gouett et al. 2011). As surface temperatures increase, global warming may become a noticeable factor that discounts construction workers' productivity.

The construction industry is susceptible to the environment, since almost 50% of the construction activities are subject to the weather influences (Benjamin and Greenwald 1973). For the construction industry as a whole, construction labor productivity is essential to both contractors and owners, since it directly correlates with the labor costs of a project. For contractors, productivity correlates with a project's profitability while for owners, productivity determines the final cost of a project. Thus, understanding the impact of global warming on construction labor productivity would be instrumental for the construction industry to be prepared to face the imminent challenges in order to respond to them as well as possible. To accomplish this objective, this study aims to develop a framework that is able to assess the impact of global warming at a project level as well as generate strategies that could accommodate the potential adverse impact of global warming.

BACKGROUND

The global warming theory is becoming more accepted by the general public in recent decades. The first primary theory of global warming identified a correlation between atmospheric concentrations of carbon dioxide and temperature and was established by a Swedish scientist, Svante Arrhenius (1859-1927), in 1896 (Maslin 2009). This theory re-emerged in the late 1980s when steep rises in the annual mean temperatures were observed (Maslin 2009). In the 1990s, scientists started questioning the theory, because of the uncertainties in the data. However, over the last two decades, the slope of the curve of the mean annual temperature remains steep and shows a strong correlation with the increase of carbon dioxide concentration in the atmosphere (Figure 4- 1). Though the debates about the theory still continue today, recent

data still sustains the global warming theory (NCDC 2013), and it is commonly accepted by a large population of scientist, politicians, economists, and the general public (Gleick et al. 2010; Jones and Henderson-Sellers 1990; McCright and Dunlap 2000).



Source: National Climatic Data Center (2013)

Figure 4- 1. The relationship between Global Temperature and Carbon Dioxide

Coupled Model Intercomparison Project (CMIP)

The Coupled Model Intercomparison Project established by the Working Group on Coupled Modeling (WGCM) under the organization of the World Climate Research Program (WCRP) aims to act as a standard experiment protocol for studying the output of coupled atmosphere-ocean general circulation models (CMIP 2013). It started in 1995 and involves a diverse community of scientists around the world. CMIP serves the entire international climate change research centers as a platform for climate model diagnosis, validation, intercomparison, and data access. This project is a continuous research effort. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) volunteers to collect the output data from the

international leading climate change research centers for archival purposes. The PCMDI's research effort is funded by both the Regional and Global Climate Modeling Program and the Biological and Environmental Program. During 2005 and 2006, PCMDI collected and archived the simulation data of the past, present, and future climate which comprises Phase 3 of the CMIP (CMIP3). This effort is the response to the World Climate Research Program (WCRP) Working Group on Coupled Modeling (WGCM)'s request for providing support for the Intergovernmental Panel on Climate Change's (IPCC) in preparation for the Fourth Assessment Report (AR4). IPCC is the leading effort in analyzing and assessing scientific information on climate change. IPCC's efforts are funded by both the World Meteorological Organization and the United Nations Environmental Program. The Phase 5 of the CMIP (CMIP5) is an ongoing effort .

Emission Scenarios for Climate Model Simulations

Greenhouse gas (GHG) emissions have been recognized as a major cause of climate change since the correlation between global warming and carbon dioxide concentration was first established by Svante Arrhenius in 1896 (Maslin 2009). The GHG emissions scenarios described in the Special Report on Emission Scenarios have been used as the standard protocol for climate change modeling. In IPCC's Third Assessment Report (TAR) (Foster 2001) and Fourth Assessment Report (AR4) (Pachauri and Reisinger 2007), six emission scenarios were described, including A1F1, A1B, A1T, A2, B1, and B2, where, A1F1, A1B, and A1T are categorized into the family of A1. The detailed descriptions of the four major emission scenarios are presented in Special Report on Emission Scenarios as follows:

- A1 scenario family describes a future world that operates in a more integrated and homogenous fashion, with rapid economic growth, low population growth, and fast adoption of new and efficient technologies.;
- A2 scenario family describes a more fragmented world, with rapid population growth and slower technological change. The economic development is self-reliant, regional-oriented, and the slowest among other scenarios;
- B1 scenario family describes a convergent and interactive world with lower population growth as A1 scenario, with rapid economic structure change toward service and IT. The future world operates in a more sustainable way with emphasis of global solutions to the three pillar of sustainability: economy, society, and environment, but without extra climate initiatives; and
- B2 scenario family depicts a world that focus on environmental protection and social equity, with the emphasis of seeking social, economic, and environmental solutions at local and regional levels, but in a sustainable way. It is a world in which population and economic growth is moderate, technological change is less rapid and more diverse than A1 and B1 scenario family.

IPCC's AR4 (Pachauri and Reisinger 2007) outlines a description of simulation experiments considering various SRES scenarios. Hereby, this paper only includes the description for three prevalent SRES experiments and their control reference, Pre-industrial control adopted by CMIP.

Pre-industrial Control (Plcntrl) is a pre-industrial simulation which provides control reference to the SRES experiments (20C3M) that will be discussed in the next few paragraphs. Pre-industrial simulation is based on a fixed level of year 1850's forcing agents, GHGs, sulfate aerosol's direct

effects and solar forcing. The parameters are: CO₂=290 ppmv, CH₄=792 ppbv, N₂O= 285 ppbv, solar constant= 1366.0 W/m², and sulfate aerosol from natural source.

SRES A1B is also called 720 ppm stabilization experiment. This experiment runs under the IPCC's emission scenario SRES A1B. It also consists of a 5-member ensemble and each simulation starts from the state of year 1990. The forcing agents are based on SRES A1B, and the concentration of the GHG are fixed at year 2100 level, for the simulations after 2100.

The *SRES A2* experiments consists of 5- member ensemble simulations as well. The initial state of the simulation is the same as SRES A1B, except for running with IPCC's SRES A2 emission scenario.

SRES B1 is often referred as to as a 550 ppm stabilization experiment. It comprises 5-member ensemble simulations and the initial state of the simulation is the same as SRES A1B.

LITERATURE REVIEW

There are large volumes of publications investigating the impact of global warming, since the theory grabbed the public's attention. The following section of the literature review focuses on the presentation of the effects of global warming in various areas, covering ecosystems, forests, human health, economy, agriculture, and construction.

Ecosystem

Healthy environmental ecosystems are in a delicate balance; small adjustment in one factor would disturb the equilibrium of the system (SHAW 1984). Thomas et al. (2004) projected the species' extinction risks from climate change. Their study was built on the well

known empirical power-law relationship that describes the relationship between the number of species and the inhabitants' areas (Rosenzweig 1995). The research effort utilized three different approaches to estimate the extinction. They sampled data from six regions including, Mexico, Queensland, South Africa, Amazonia, Cerrado, and Europe. Based on the mid-range climate-change scenarios, it was found that, by 2050, 15 to 37% of the species in sampled regions would be at the risk of extinction. Extinction of a specie could cause the ripple effect of the whole food chain, causing damage to the whole system until a new state of equilibrium is established (Casper 2009).

Forestry

Global warming is expected to result in a forests poleward migration and a change in the composition of tree species (Cline 1992). Using Holdridge Life Zone classification system and general circulation model (GCM) projections, Sedjo and Solomon (1991) estimated the impact of doubled CO₂ scenario on forest change. They found that the biomass for boreal and temperate forest would decline by 40% and 1.3%, respectively, while the biomass for tropical forests would increase by 12%. The global net change would be an overall 3.7% decrease in biomass and a 5.8% decline in vegetation areas throughout the globe. A similar nature study performed by the Environment Protection Agency (EPA 1989) indicated that the forest in the U.S. Great Lake Region could lose 23 to 54% of biomass, and U.S. Western Forests would lose 40%. The overall loss of the U.S. forests could amount to 40% considering a potential scenario of a doubling of atmospheric carbon dioxide (Sedjo and Solomon 1991).

Human Health

Amongst the possible impacts of global warming, those on human health are one of the biggest concerns (Bosello et al. 2006; Smith et al. 2001). Bosello (2006) summarized the expected health impact due to global warming, which includes increased heat-related problems affecting people with pre-conditioned cardiovascular and respiratory disorders, reduced cold-related illnesses, affected range and abundance of species carrying diseases, and virulence of diseases. Climate change also increases the chance of diseases invading immunologically low populations with insufficient medical system. Climate change would affect water-borne diseases, such as cholera and diarrhea as well (A.J. McMichael 2001).

Agriculture

Global warming is anticipated to cause crops' productivity loss in many regions while it may actually increase productivity in others (Cline 1992). The primary reasons for the productivity losses are increased heat stress, decreased soil moisture, and shortened growing cycle for crops. In the 1990s, a number of studies (Darwin et al. 1995; Fischer et al. 1995; Kane et al. 1992; Reilly et al. 1994; Tsigas et al. 1997) used different models and scenarios to estimate the impact of global warming on the agriculture industry by measuring the change of gross agriculture products. Nine regions were assessed including, OECD-America (except Mexico) (OECD-A), OECD-Europe (OECD-E), OECD-Pacific (except South Korea) (OECD-P), Central and Eastern Europe and the former Soviet Union (CEE&fSU), Middle East (ME), Latin America (LA), South and Southeast Asia (S&SEA), Centrally Planned Asia (CPA), and Africa (AFR). The results and assumptions are presented in Table 4- 1.

Table 4- 1. Estimates of the Impact of Climate Change on Agriculture (2.5 °C increase in the global mean temperature, percent of gross agriculture product)

Study	Kane		Tsigas		Darwin		Reilly		Fisher	
550 CO ₂ ?	No	No	Yes	No	No	Yes	Yes	No	Yes	Yes
Adaption ?	No	No	No	Yes	No	No	Yes	No	No	Yes
OECD-A	0.03	-0.31	0.05	0.10	0.03	0.00	0.00	-8.83	-2.38	-0.58
OECD-E	-0.52	-0.73	0.14	-0.41	-0.34	-0.06	-0.02	-7.10	0.55	2.60
OECD-P	-2.08	-1.38	-0.06	0.31	-0.31	-0.04	-0.01	-3.24	-0.28	0.49
CEE & fSU	-0.02	-1.48	-0.07	0.14	-0.18	-0.25	-0.18	-6.84	1.65	3.32
ME	-0.01	-1.48	-0.07	0.14	-0.18	-0.25	-0.18	-9.09	-2.97	-1.93
LA	0.05	-2.18	-0.47	0.10	-0.22	-0.15	-0.16	-13.13	-4.33	-3.08
S&SEA	-0.08	-2.26	-0.32	-0.04	-0.91	-0.17	-0.13	-12.04	-4.00	-2.76
CPA	3.84	-3.97	0.28	0.11	-10.09	0.04	0.53	-1.20	0.82	1.07
AFR	-0.01	-1.48	-0.07	0.14	-1.18	-0.25	-0.18	-5.31	-1.71	-1.11

Sources: After Kane et al. (1992), Tsigas et al. (1996), Darwin et al. (1995), Reilly et al. (1995) and Fisher et al. (1993)

Economic Impact

Climate change affects agriculture, forestry, fishery, energy use, health, and other aspects of nature that in turn can affect every living being on this earth. In order to understand the effects, a collection of economists have attempted to estimate the effect of climate change on the global economy. Tol (2009) summarized the results of the studies performed by a number of researchers (Fankhauser 1995; Hope 2006; Maddison 2003; Mendelsohn et al. 2000; Nordhaus 1994; Nordhaus 1994; Nordhaus 2006; Nordhaus and Boyer 2003; Nordhaus and Yang 1996; Plambeck and Hope 1996; Rehdanz and Maddison 2005; Richard 1995; Tol 2002) since 1990s. Though the studies used different methods and warming scenarios with different temperature increases, they show a large degree of agreement on some points (Tol 2009). Asia(w/o China), South America, Africa, and China are the regions that would experience the most impact, while Eastern Europe and the former Soviet Union would experience the least impact or have some benefits from global warming. However, global warming affects the overall global economy in a negative way.

Construction Industry

Although there are large volumes of research studies on global warming, the impact of global warming on the global construction sector has been rarely studied. For the regions that have winter seasons with subfreezing temperatures, intuitive thinking may lead to the conclusion that global warming would prolong the construction season by increasing the number of days with above freezing temperatures, thus increases productivity (Cline 1992). However, global warming may also produce heat waves in summers that may prevent construction workforces from working efficiently. In addition, global warming increases rainfalls in some regions. In the UK, "rainfall is responsible for more delays than any other climatic variable" in the construction industry (Cline 1992). The overall impact of global warming on the global construction sector remains unclear, because it depends on whether the benefits of lengthened construction season would outweigh the damage of hot summers and increased precipitations, if applicable.

Global Warming Impact on Regional Labor Productivity

Global warming can influence human activities, thus affect labor productivity. Kjellstrom et al. (2009) studied the direct impact of global warming on labor productivity in various regions across the globe. The whole study was based on the relationship between work capacity(%), work intensity, and wet bulb global temperature(WBGT). WBGT is the heat index that is used as a reference to determine the break time that should be inserted after a period of time of work to avoid heat stress imposed on workers. The work capacity defined by Kjellstrom et al. (2009) is the percentage of the work time that accounts for the total time including both work and break time. The authors effort sampled a reasonable number of grid points of every region across the globe and obtained the projected daily climate model data in 2020s, 2050s, and 2080s. By cross-referencing the industry composition of each region, the authors could

approximate the work intensities for the working population involved in each region. With all of the available data, the work capacity losses due to temperature were computed and compared with the baseline.

POINT OF DEPARTURE

A large amount of construction activities are undertaken in an outdoor environment. Global warming will result in climate changes including temperature and humidity that affect the construction workers' productivity. The implication of global warming on the construction industry has rarely been studied. Although people speculate that the construction industry may experience productivity gains because of prolonged construction seasons, this speculation appears premature since elevated temperatures beyond human comfort levels decrease productivity, which may cancel out the productivity gains that global warming could possibly bring.

This research departs from the overall body of knowledge by utilizing a novel framework to examine the impact of temperature and humidity on construction labor productivity at a project level considering the effects of forecasted global warming trends using a building information modeling (BIM)-based simulation approach. This research is built upon the established knowledge about the construction labor productivity as a function of temperature and humidity, and utilizes temperature and humidity projections predicted by prevalent global climate models (GCMs). The described research distinguishes itself from Kjellstrom et al. (2009) in the following aspects:

- 1) This dissertation focus on a micro level, project level, analysis.

2) This dissertation approaches construction labor productivity as a function of temperature and humidity, instead of using work capacity relative to WBGT, because of the limitations inherited in Kjellstron et al.'s (2009) study. For instance, their labor productivity model only addresses the hot working environments not cold environments, and work capacity may not be a good indicator of labor productivity.

3) This research is also part of a pioneering study that integrates the labor productivity information with BIM to demonstrate a more comprehensive approach to productivity analyses.

SCOPE OF RESEARCH

The objective of this dissertation is to formulate a framework that can be used to estimate the forecasted global warming's impact on construction labor productivity at a project level in different regions around the world. This research limits its scope to steel craft workers. The research effort exclusively focus on steel trades for the following reasons:

- 1) Steel erection are outdoor activities that are subject to temperature and humidity effect;
- 2) Steel erection activities are usually on the critical path of the entire project;
- 3) Steel erection are up front activities prior to other trades' work, therefore, it is less likely to be affected by other activities which otherwise would complicate the research by introducing "noises" to the study; and
- 4) CIMsteel Integration Standards(CIS/2), the current BIM standards for steel trades, is well implemented by the BIM software vendors in order to ensure the seamless information exchange between different BIM applications

This study uses the steel structure model of the first phase of the University of Kentucky Albert B. Chandler Hospital Pavilion project as the prototypical model to develop the described framework. The project's construction started in 2009 and completed in spring 2011, with a total square footage of 1.2 million square feet and the total cost of 532 million dollars. The Turner Construction Company was the project's construction manager. The total building has a 5-story podium plus one story of basement and two 8-story towers. The basement and podium were constructed with reinforced concrete, while the structure of the two towers utilized structural steel. The hospital contains 512 private patient rooms, 28 surgery rooms, emergency rooms, and other family support areas including food service, gift, and coffee shop.

The author readily acknowledge that global warming could possibly shift other weather patterns, such as wind and precipitation. However, this research just focuses on the temperature and humidity effects only, and other weather's impact on schedule is not considered , which also acts as a control for inter-regional comparison about the temperature and humidity's effect subject to the influence of global warming.

RESEARCH METHODS

To accomplish the proposed objective of this research, the following steps are followed to orchestrate the framework of this study:

- 1) Use ConstructSimTM to convert the CIS/2 formatted model of the steel structure of the UK hospital project into a virtual construction model, and assign work hours to model objects by referencing unit rate productivity information;

- 2) Select an appropriate model that describes the labor productivity relative to temperature and humidity;
- 3) Obtain temperature and humidity projection data for selected cities around the world between the years 2050 to 2099 with respect to two GCM models and four emission scenarios including A1b, A2, B2, and Pre-industrial Control(Pinctrl). Obtain historical temperature and humidity data from 2001 to 2010 for the selected cities and treat them as current climate scenarios;
- 4) Calculate productivity factors based on the selected labor productivity model describing the relation to temperature and humidity;
- 5) Develop a baseline schedule (without temperature and humidity effects) according to the construction activities' sequence that was taken place at the real project;
- 6) Use VBA scripts built in Excel to integrate the CPM schedule with man power sources and productivity factors considering the temperature and humidity to automate the process of schedule simulation;
- 7) Use the simulation interface to simulate the impacts of temperature and humidity effect under forecasted global warming trends to generate the work hours required to build the model project; and
- 8) Perform statistical analyses of the simulation results to generate knowledge about global warming impact.

Virtual Construction Modeling

The process of virtual construction modeling is a process of retaining information of an upstream design model and assigning additional information that is instrumental for planning,

monitoring, and tracking the construction activities while removing construction irrelevant information. ConstructSimTM, one of the Bentley's BIM software suites, was used for the purpose of building the virtual construction model.

In this described research, the process of virtual construction modeling involves two major processes: CAD processing and model processing. The readers can refer to the workflow as described in Chapter 3's Figure 3-5. CAD processing is to map the neutral data formatted CAD model into the data structure that can be understood by ConstructSimTM. During the process of model processing, the work hour information associated with each steel member is automatically populated by cross-referencing a unit rate productivity table through a series of relational SQL database tables. The unit rate labor productivity was obtained from Richardson's Construction Estimating Standards(Richardson 2013). The other process involved in the model processing is a task processing, where users can break a steel installation activity into the typical steps and specify the percentage of time spent on each step measured against the whole installation time. For this study, the research effort broke the steel installation activity into two steps: erection and detailing. Erection includes the activities from material unloading and handling to initial bolt up; and detailing includes plumbing/leveling, bolt tightening, and final welding. According to the onsite steel erection log of the UK hospital project, approximately 75% of the time was used on erection and 25% on detailing.

Develop Baseline Schedule

With all of the work hour information populated in the virtual construction model, the next step is to develop a baseline schedule without considering the negative effects of temperature and humidity. The CPM schedule is developed based on the precedence of activities

and the labor resources assigned on each working area obtained from the construction activity log on steel erection. The task units of the schedule for this study are individual work packages. Work package is a typical task unit within the domain of a lower level scheduling, usually at the crew level, which aims to break a complex project into manageable components on the jobsite. A work package usually represents the work that can be done by a crew in a week; it ranges from 400 to 1000 work hours depending on the crew size(CII 2012). More elaborative descriptions about work packaging can be referred to Section "Develop Work Package " in Chapter 3.

Global Warming Data Collection

To control the scope of this dissertation research, two models out of the 26 models from various climate research centers were picked for the source of climatic projection data. In addition, two different models allow comparisons and cross-validations of the results. To obtain the needed dataset, the following criteria were used during the process of selection:

- 1) The dataset generated from the models must contain the variables of temperature and relative humidity;
- 2) The models must have the pre-industrial control, SRES A1B, A2, and B1 simulations;
and
- 3) The models from each climate center should represent the most recent model.

Based on the above criteria, this research effort decided to use the National Oceanic and Atmospheric Administration's (NOAA's) Climate Model CM2.1 and Hadley Center for Climate Prediction's Coupled Model Version 3 (HADCM3). NOAA is a scientific agency under the administration of Department of Commerce focusing on the conditions of the atmosphere and oceans, headquartered in Silver Spring, Maryland in the U.S., and Hadley Center is based in the

U.K. Both models can be considered as robust models and are widely cited by a great number of research studies from different areas (Barnett et al. 2005; Battin et al. 2007; Kjellstrom et al. 2009; Krawchuk et al. 2009; Vecchi et al. 2006).

Sampled Locations for Study

Global warming has varied impact on a global scale. According to Environmental Protection Agency's (EPA 2012) report on international impacts and adaption due to climate change, Africa and Asian appear to be the most vulnerable regions. In terms of economy, Brazil, Russia, India, and China, also known as the BRIC countries, are the four largest developing countries and anticipated to experience the largest economy growth in the 21st century (Global Sherpa 2013). Understanding the potential impact of global warming would be of more importance to BRIC countries. To investigate the potential impacts of global warming trends on construction productivity at various geographical locations, the research effort decided to select a number of major cities from different continents, BRIC countries included. The selection of the cities is based on the following criteria: 1) the cities should include a large scale of population and economy relative to the countries where they are located and 2) the cumulative annual precipitation should not exceed 1500 mm. The research effort included the second criteria because the perception effect is not considered in this study, and the research effort want to remove the "noise effect" due to excessive rainfalls. With the described criteria in mind and reference to the affect regions described in EPA's report, the research effort selected following cities, Khartoum, the capital city of Sudan, Delhi, the second largest city in India, Houston, US, Melbourne, the second largest city in Australia, Brasilia, the capital city of Brazil, Chongqing, the fourth direct-controlled municipalities of China, and Moscow, the capital city of Russia (Figure 4- 2).



Figure 4- 2. Geographic Locations of the Sampled Cities

Obtain Grid Point Data on Temperature and Humidity

All the projection data between years 2050 to 2099 used for this study were obtained from the WCRP CMIP3's data portal (WCRP 2013) . The datasets are in Network Common Data Form (NetCDF), a type of machine independent data format that commonly used by geospatial scientific research for storing array-oriented scientific data (OGC 2013). To obtain temperature and humidity simulation data for the sampled cities, the research effort used the ArcGIS software package to extract the interested variables from the grid points corresponding to each city.

Historical Weather Data Collection

The research effort also downloaded the 2001-2010 historical temperature and humidity data, representing current climate scenarios, from Weather Underground for the later schedule simulation input as well. Comparing future scenarios with current climate scenarios can clarify the implication of global warming's impact on the current construction industry. This type of comparison also could draw a conclusion that might resonate with readers better.

Labor Productivity vs. Climate Model Selection

The next step is to use the obtained temperature and humidity data to relate with labor productivity. Through a literature review of different models describing the relationship between labor productivity and climatic conditions, the research effort decided to use Koehn and Brown's (1985) model because of the large sample size, broad range of temperature and humidity scenarios, and the variety of the trades involved in the data collection. The relationship between productivity factor and temperature and humidity is tabulated in Table 4- 2

Table 4- 2. Construction Productivity as Function of Temperature and Relative Humidity

Temperature (°F)	Relative Humidity (%)									
	5	15	25	35	45	55	65	75	85	95
-20	0.28	0.27	0.25	0.22	0.18	0.13	0.05	-	-	-
-10	0.44	0.43	0.42	0.40	0.38	0.34	0.29	0.21	0.10	-
0	0.59	0.58	0.57	0.56	0.54	0.52	0.49	0.44	0.36	0.23
10	0.71	0.71	0.70	0.70	0.69	0.67	0.65	0.62	0.58	0.50
20	0.81	0.81	0.81	0.81	0.81	0.80	0.79	0.77	0.75	0.71
30	0.90	0.90	0.90	0.90	0.90	0.89	0.89	0.89	0.88	0.87
40	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96	0.96
50	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
60	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
70	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
80	1.00	1.00	1.00	1.00	1.00	0.99	0.98	0.96	0.95	0.93
90	0.95	0.95	0.94	0.93	0.92	0.90	0.88	0.85	0.82	0.78
100	0.81	0.81	0.80	0.79	0.77	0.74	0.71	0.67	0.61	0.54
110	0.58	0.58	0.58	0.57	0.55	0.51	0.47	0.41	0.32	0.21
120	-	0.28	0.28	0.28	0.25	0.21	0.15	0.07	-	-

Note: . The productivity factor is defined as the ratio of estimated baseline productivity to productivity subject to temperature and humidity effects.

Although there are three other studies (Grimm and Wagner 1974; NECA 1974; Thomas and Yiakoumis 1987) that examined the relationship between labor productivity and temperature and humidity, the research effort did not adopt them because of the major limitations of their model application. Grimm and Wanger's (1974) model is only good for productivity predictions when temperatures are at the range of 40 to 100 °F, and relative humidity from 20 to 100%.

Thomas and Yiakoumis' (1987) model bears the similar limitation that goodness of the model is

limited by the temperature range, from 12 to 82 °F. NECA's(1974) model is developed by solely examining a single electrical activity, and the intensity of the work is not comparable to steel erection.

In Kjellstron et al.'s (2009) article titled "*The Direct Impact of Climate Change on Regional Labor Productivity*", work capacity as a function of WBGT was used. WBGT is used as the heat index to insert required breaks between the work to protect workers from heat related illness. Kjellstron et al.'s (2009) equated the work capacity as the proxy of labor productivity, which might not be necessarily accurate. Heat affects workers not only physically but also psychologically. Kjellstron et al.'s model did not account the productivity loss due to the lack of interest of work because of the heat's psychological effect. Workers may appear to be at the state of working but may not be as productive as under a more comfortable temperature. WBGT does not address productivity loss due to cold temperature either. Therefore, in Kjellstron et al.'s (2009) study, productivity losses under cold days were not accounted. This is also the reason why this research effort wanted to take a different approach to the described study.

Having obtained the historical temperature and humidity data and the projection data from 2050 to 2099 with the consideration of the following scenarios, including pre-industrial control, SRES A1B, A2, and B1, the research effort can compute the corresponding labor productivity factors through Koehn and Brown's (1985) model (Table 4- 2). Ultimately, productivity factors with respect to the timeline can be attained.

Simulation of Temperature and Humidity Impact on Schedule

For this study, the research effort used the simulation interface developed in Chapter 3 to simulate the temperature and humidity impact on the hospital project's schedule performance. Detailed information regarding the simulation algorithm can be referred to Section "Algorithm of Schedule Simulation", in Chapter 3.

The simulation interface is able to simulate the temperature and humidity effect on labor productivity and automatically adjust the CPM schedule. Once a project start date is selected for simulation, the interface would generate the start and finish dates for each task as well as the duration, and the work hours required for each task and the entire steel structural project. For this study, the research effort set the simulation starting dates on the first day of each quarter, i.e. January 1st, April 1st, July 1st, and October 1st for each geographic location, which allows exposure to temperature and humidity shifts due to season for each location.

Statistical Tests

With generated simulation results in work hours required to build the model project, a series of statistical analyses were performed to generate instrumental knowledge about the implications of global warming to the construction industry. The following tests were performed through statistical analyses:

- 1) To test if using the projection data from two climate models (HADCM3 and NOAA CM2.1) would generate significantly different simulation results;
- 2) For each climate model, test if the emission scenarios (SRES A1B, A2, and B1) produce significantly different estimates about the work hours required to build the project;

3) For each climate model and emission scenario, perform 2-way ANOVA involving 3 sub-test:

a) if there is significant difference in required work hours to build the model project among different project starting date groups when examining one location at a time;

b) if there is significant difference in required work hours to build the model project among different project location groups when examining one project start date at a time; and

c) if there is interaction between project location and start date;.

4i) To test the work hour mean difference between each emission scenario and pre-industrial control during 2090s with respect to different climate models across sampled cities; and

4ii) To test the work hour mean difference between each emission scenario during 2090s scenarios with respect to different climate models and current climate scenarios across sampled cities.

RESULTS OF STATISTICAL ANALYSES

Model Difference (HADCM3 model vs NOAA CM2.1)

Instead of relying on a single model to examine the possible impact of global warming on the work hours required to build the model project, the research effort used two models and compared the difference of the results generated by them. For this comparison, the research effort used the climate projection data during year 2050 to 2099 forecasted by both HADCM3 and NOAA CM2.1 models. Table 4-3 and Figure 4- 3 describe the required work hours and their differences for each emission scenario between the two models across the 7 selected locations.

The Student's t-tests were used to test the mean difference between two groups. The Student's t-test is a parametric method, and one of the assumptions for the test is the assumption of normality of data. The research effort used the technique of Bootstrap to resample the data, such that unnecessary assumption of data's normality can be avoided. Because of the amiable temperature and humidity presented in Melbourne, the work hour difference in Melbourne does not vary much, therefore the tests were not performed for Melbourne. The tests show that for most of the cases, both models result in statistical significant difference in the mean work hours required to build the project except the cases, Khartoum's Pinctrl, and Delhi's A1b, A2 and B1. Though statistically significant difference due to climate model difference were observed for Houston and Brasilia, on average the resulted discrepancies in work hour estimates between the models are below 1000. For Houston and Moscow, the estimates of work hours using HADCM3 climate model are at least 1000 greater than using NOAA CM2.1 model; and the discrepancies between the two models for Moscow are even greater. Among the cases with statistically significant differences for both Khartoum and Delhi, the differences between the models for are moderate in terms of work hours required to build the model project.

Table 4-3. The Comparison of Simulated Work Hour Difference by Model with 2050-2099 Projection Data (HADCM3 vs. NOAACM2.1)

Location	Scenario	Work Hours			
		HADCM3	NOAA CM2.1	Difference	sig
Khartoum	Pinctrl	55,746	55,701	45	0.563 ^a
	A1b	58,881	59,923	-1,041	0.002
	A2	59,422	60,257	-835	0.005
	B1	57,749	58,357	-608	0.001
Delhi	Pinctrl	57,407	56,260	1,147	0.001
	A1b	60,665	59,909	756	0.081 ^a
	A2	60,299	60,075	224	0.585 ^a
	B1	59,402	58,884	517	0.145 ^a
Houston	Pinctrl	56,222	55,218	1,003	0.001
	A1b	59,419	56,398	3,021	0.001
	A2	58,864	56,527	2,337	0.001
	B1	58,290	55,992	2,298	0.001
Melbourne	Pinctrl	54,338	54,343	-5	N/A
	A1b	54,338	54,338	0	N/A
	A2	54,338	54,340	-2	N/A
	B1	54,338	54,338	0	N/A
Brasilia	Pinctrl	54,936	54,511	425	0.001
	A1b	56,481	55,580	901	0.001
	A2	56,196	55,693	502	0.001
	B1	56,093	55,194	899	0.001
Chongqing	Pinctrl	55,128	55,852	-724	0.001
	A1b	55,213	55,372	-159	0.004
	A2	55,102	55,480	-378	0.001
	B1	55,151	55,516	-365	0.001
Moscow	Pinctrl	71,033	66,092	4,941	0.001
	A1b	63,043	59,877	3,166	0.001
	A2	64,687	59,896	4,791	0.001
	B1	64,967	61,359	3,608	0.001

Note: The Student- T tests were performed on the data subject to the technique of bootstrap

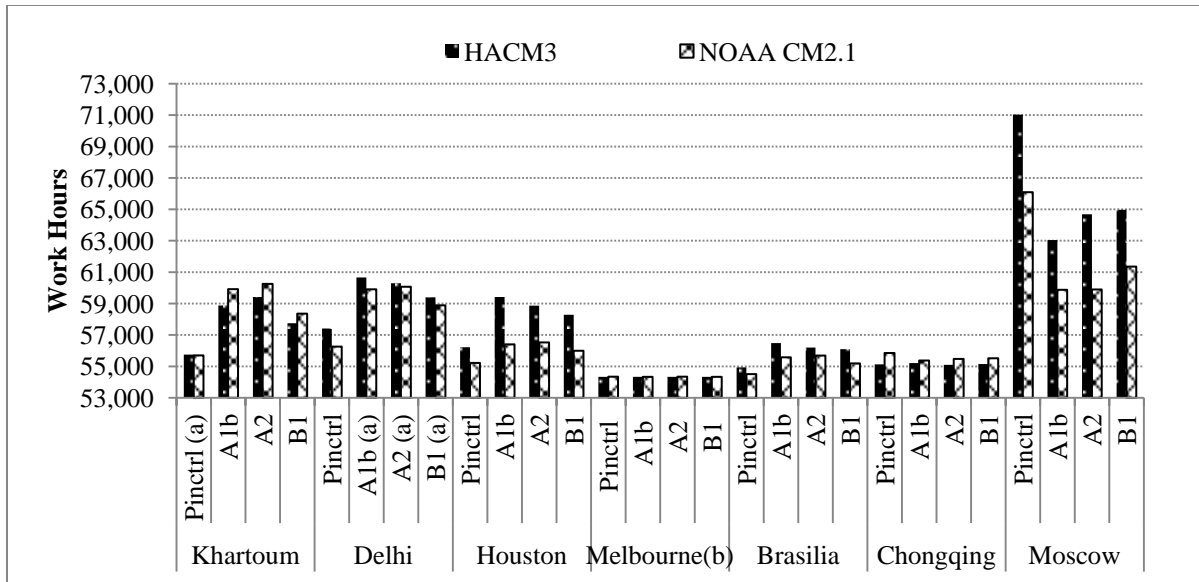
^a Differences are not statistically significant at the 95% confidence level.

Acronyms:

HADCM3: Hadley Center Coupled Model, Version 3

NOAA CM2.1: National Oceanic and Atmospheric Administration Coupled Model, Version 2.1

Pinctrl: Pre-industrial Control



Note: (a) Difference between models is statistically significant.

(b) statistical test were not able to be performed

Figure 4- 3. Work Hour Estimates for Each Emission Scenario Across the Locations with 2050-2099 Projection Data (HADCM3 & NOAA CM2.1)

Difference Among GHG Emission Scenarios

This section investigates the differences in required work hours attributed to the GHG emission scenarios. Since HADCM3 and NOAA CM2.1 model contribute to significant differences in required work hours for most of the emission scenario across the seven cities, the research effort examined the difference among three emission scenarios, A1b, A2, and B1, with respect to each climate model across seven cities. Considering the non-normality of the data, the research effort used nonparametric method, Kruskal-Wallis, to detect the difference in the distribution of the work hour estimates across categories of emission scenarios with respect to both climate models using the climate projection data during 2050 to 2099. Table 4- 4 to Figure 4- 5 describe the descriptive statistics and statistical test results. For the HADCM3 model, among the seven cities only Moscow did not experience statistically significant difference in the distribution of the work hour estimates across the three GHG emission scenario; the Krusal-

Wallis test was not performed on Melbourne because the three emission scenario produced the same results across the board. As to the Model NOAA CM2.1, all of the locations experienced statistically significant difference in the distribution of the work hour estimates across the three emission scenarios except Moscow. As shown in Figure 4- 4 and Figure 4- 5, on average the work hours required to build the project in Moscow is the greatest compared to other locations; Melbourne requires the minimal work hours to built the model project, followed by Chongqing and Brasilia.

Table 4- 4. The Krusal-Wallis Test for the Distribution of Work Hours Across Emission Scenarios with HADCM3 Model (2050 -2099 Projection) by Location

Location	Work Hour (Mean)			Krusal-Wallis Test	
	A1b	A2	B1	Test Statistics(K)	Sig
Khartoum	58,881	59,422	57,749	40.43	0.000
Delhi	60,665	60,299	59,402	9.34	0.009
Houston	59,419	58,864	58,290	8.64	0.013
Melbourne	54,338	54,338	54,338	-	-
Brasilia	56,481	56,196	56,093	6.78	0.034
Chongqing	55,213	55,102	55,151	11.95	0.003
Moscow	63,043	64,687	64,967	4.73	0.094 ^a

^a. Result is not statistically significant at the 95% confidence level.

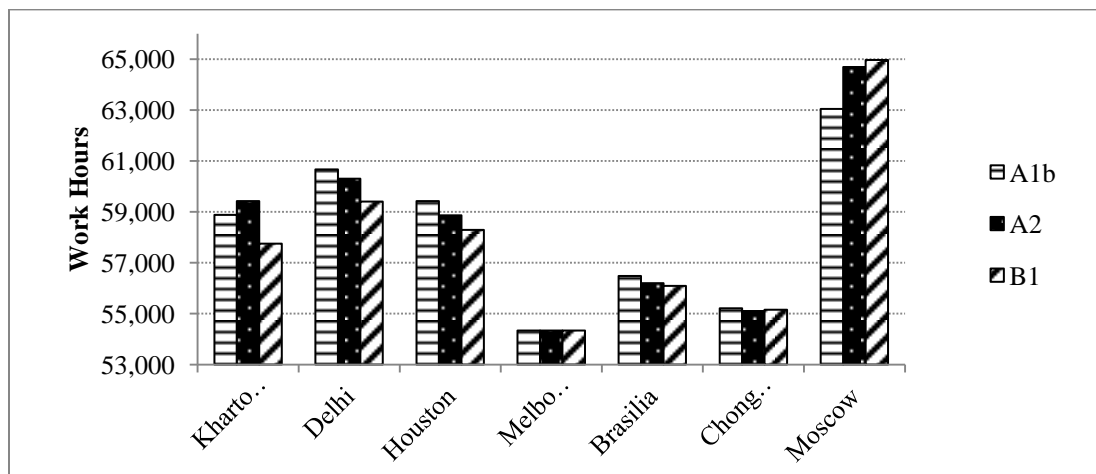


Figure 4- 4. Mean of the Work Hours Estimates for Each Emission Scenario Across Seven Cities with HADCM3 2050-2099 Projection Data

Table 4- 5. The Krusal-Wallis Test for the Distribution of Work Hour Estimates Across Emission Scenarios with NOAA CM2.1 Model (2050 -2099 Projection) by Location

Location	Work Hour (Mean)			Krusal-Wallis Test	
	A1b	A2	B1	Test Statistics(K)	Sig
Khartoum	59,923	60,257	58,357	50.99	0.000
Delhi	59,909	60,075	58,884	14.07	0.001
Houston	56,398	56,527	55,992	17.58	0.000
Melbourne	54,338	54,340	54,338	65.345	0.000
Brasilia	55,580	55,693	55,194	47.30	0.000
Chongqing	55,372	55,480	55,516	3.87	0.145 ^a
Moscow	59,877	59,896	61,359	11.38	0.003

^a. Result is not statistically significant at the 95% confidence level.

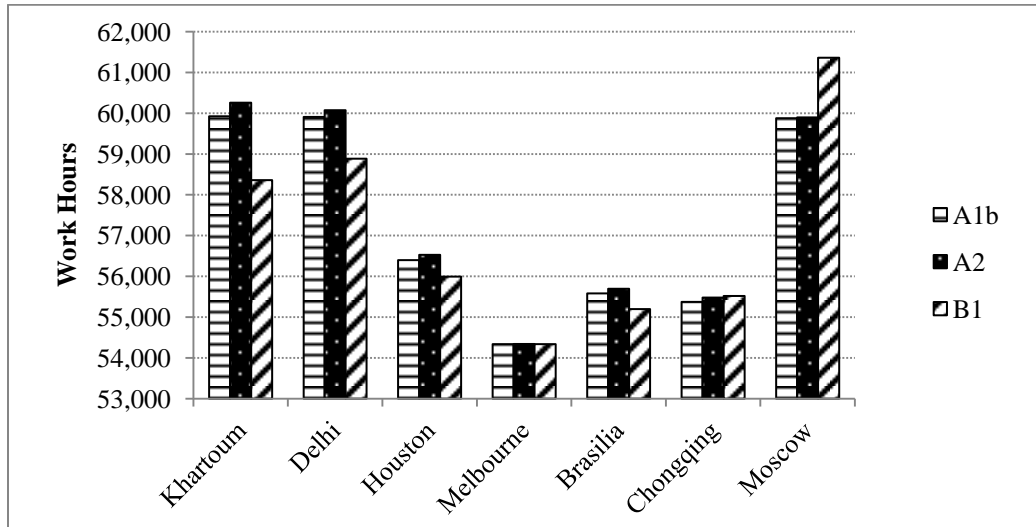


Figure 4- 5. Mean of the Work Hour Estimates for Each Emission Scenario Across Seven Cities with NOAA CM2.1 2050-2099 Projection Data

Project Start Date and Location 2-Way ANOVA

This section briefly presents the result of 2- way ANOVA, examining the effects of project start date and location on the work hours required to build the model project. As earlier described, the model project was situated in seven global cities with project start date set on the first day of each quarter. For this analysis, the climate project data collect throughout 2050 to 2099 were used. Above analyses have shown that, by and large, significant differences were

observed between the models and among the various emission scenarios. Therefore, when 2-way ANOVA's were performed, the research effort examined every emission scenario under each climate model separately. For the sake of the size limit of this chapter, the authors included the detailed figures and tables pertain to the analyses in the Appendix IV. For each climate model and emission scenario, all of the analyses show that there are statistically significant differences observed in the work hour estimates among the project start date groups; statistically significant differences were also observed among the project location groups; and that interaction effects between project start date and location were observed as well.

Global Warming Scenarios vs. Pinctrl

As global warming theory has attributed the major causes of global warming to the industrial development, the authors investigated the difference in work hour estimates between the three future emission scenarios and pre-industrial (Pinctrl) control. The simulation of Pinctrl is based on the assumption that forcing agents are fixed at the level of 1850. *The purpose of comparing the difference with Pinctrl is to understand the loss of productivity during the whole process of industrialization in the construction industry.* For this part of the study, 2090s' projection data of both HADCM3 and NOAA CM2.1 models were used. Table 4- 6 and Figure 4- 6 illustrate the comparison of work hours required to build the model project between three global warming scenarios and Pinctrl using the Model HADCM3. Table 4- 7 and Figure 4- 7 illustrate the comparison of work hours required to build the model project between three global warming scenarios and Pinctrl using the Model NOAA CM2.1. To test the statistical significance, Student's-t tests were performed on the data subject to bootstrap. Those differences that are not statistically significant at the 95% confidence level are specifically noted. Though HADCM3 and NOAA CM 2.1 show some discrepancies in the results, the trend of the results, by and large,

agrees with each other except that the discrepancy for Houston between the models are quite substantial. Set Houston aside as a particular case; both Figure 4- 6 and Figure 4- 7 show that the work hours required to build the model project in Khartoum, Sudan, and Delhi, India increase remarkably under the consideration of global warming with both climate models compared to the scenario of Pinctrl. The increased percentage for Khartoum ranges from 4.2 to 11.9% depending on the emission scenario and model used for simulation, while the increased percentage for Delhi ranges from 5.0 to 10.2%. On average for those two cities, Model NOAACM2.1 tends to produce higher estimates than Model HADCM3 does across the three emission scenarios. Brasilia would experience a moderate increase in the work hours required to build the project, ranging from 1.2 to 3.9%. From the statistical results, Melbourne and Chongqing would experience the least impact from the global warming. Comparing 2090s' climate scenarios to Pinctrl, on average Moscow would experience significant decreases in the work hours required to build the model project, which suggests a significant productivity gain, and the results are statistically significant at the 95% confidence level.

Table 4- 6. Comparisons between Global Warming Scenarios and Pre-industrial Control (Model HADCM3 2090s' Data)

Location	Work Hour			A1b-Pinctrl				A2-Pinctrl			B1-Pinctrl		
	A1b	A2	B1	Pinctrl	Diff.	%	Sig.	Diff.	%	Sig.	Diff.	%	Sig.
Khartoum	59,638	61,246	58,007	55,660	3,978	7.1%	0.001	5,585	10.0%	0.001	2,346	4.2%	0.001
Delhi	61,167	61,460	60,385	57,605	3,562	6.2%	0.001	3,855	6.7%	0.001	2,780	4.8%	0.007
Houston	60,349	60,456	59,052	55,798	4,551	8.2%	0.001	4,657	8.3%	0.001	3,253	5.8%	0.001
Melbourne ^b	54,338	54,338	54,338	54,338	-	0.0%	NA	-	0.0%	NA	-	0.0%	NA
Brasilia	57,043	56,942	56,359	54,916	2,127	3.9%	0.001	2,027	3.7%	0.001	1,443	2.6%	0.001
Chongqing	55,275	55,221	55,231	55,211	64	0.1%	0.142 ^a	10	0.0%	0.947 ^a	20	0.0%	0.844 ^a
Moscow	60,885	62,595	63,692	71,252	(10,366)	-14.5%	0.001	(8,657)	-12.1%	0.003	(7,560)	-10.6%	0.005

^a. Result is not statistically significant at the 95% confidence level.

^b. Student's-t test could not be performed.

Table 4- 7. Comparisons between Global Warming Scenarios and Pre-industrial Control (Model NOAA CM2.1 2090s' Data)

Location	Work Hour			A1b-Pinctrl				A2-Pinctrl			B1-Pinctrl		
	A1b	A2	B1	Pinctrl	Diff.	%	Sig.	Diff.	%	Sig.	Diff.	%	Sig.
Khartoum	60,638	62,324	58,709	55,683	4,955	8.9%	0.001	6,641	11.9%	0.001	3,026	5.4%	0.001
Delhi	60,960	61,908	58,968	56,177	4,783	8.5%	0.001	5,731	10.2%	0.001	2,791	5.0%	0.001
Houston	56,703	57,077	56,122	55,253	1,450	2.6%	0.001	1,824	3.3%	0.001	868	1.6%	0.001
Melbourne	54,338	54,341	54,338	54,341	(3)	0.0%	0.036	(0)	0.0%	0.806 ^a	(3)	0.0%	0.036
Brasilia	55,697	56,129	55,189	54,559	1,138	2.1%	0.001	1,570	2.9%	0.001	630	1.2%	0.001
Chongqing	55,342	55,480	55,456	55,834	(493)	-0.9%	0.032	(354)	-0.6%	0.128 ^a	(378)	-0.7%	0.111 ^a
Moscow	58,437	58,296	60,807	65,649	(7,212)	-11.0%	0.001	(7,353)	-11.2%	0.001	(4,842)	-7.4%	0.013

^a. Result is not statistically significant at the 95% confidence level.

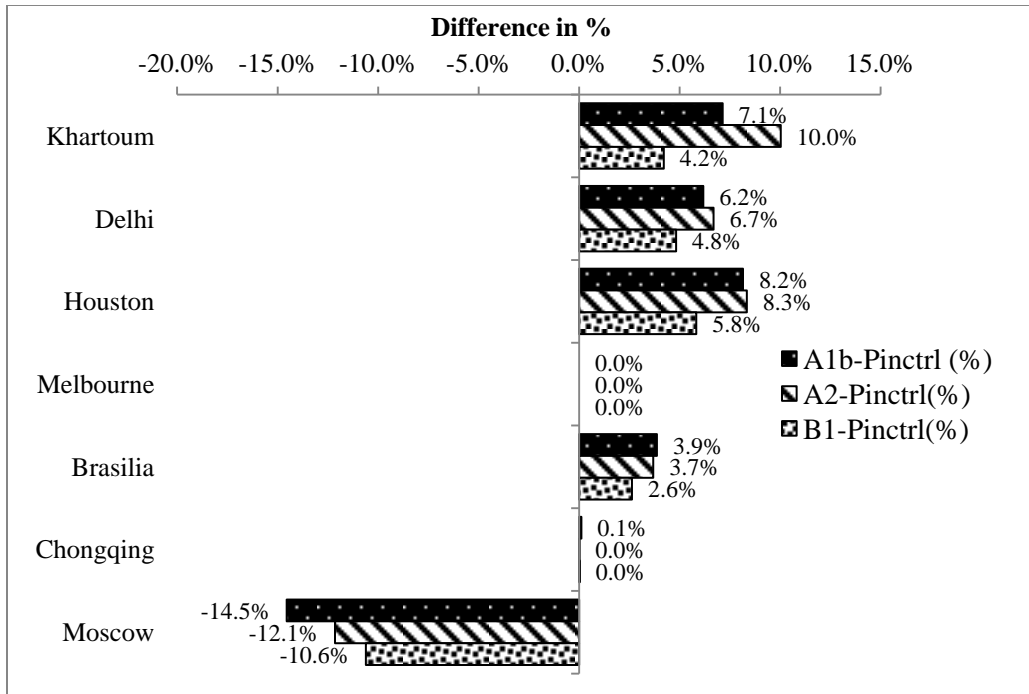


Figure 4- 6. Work Hour Difference in Percentage between Global Warming Scenarios and Pre-industrial Control (Model HADCM3 2090s' Data)

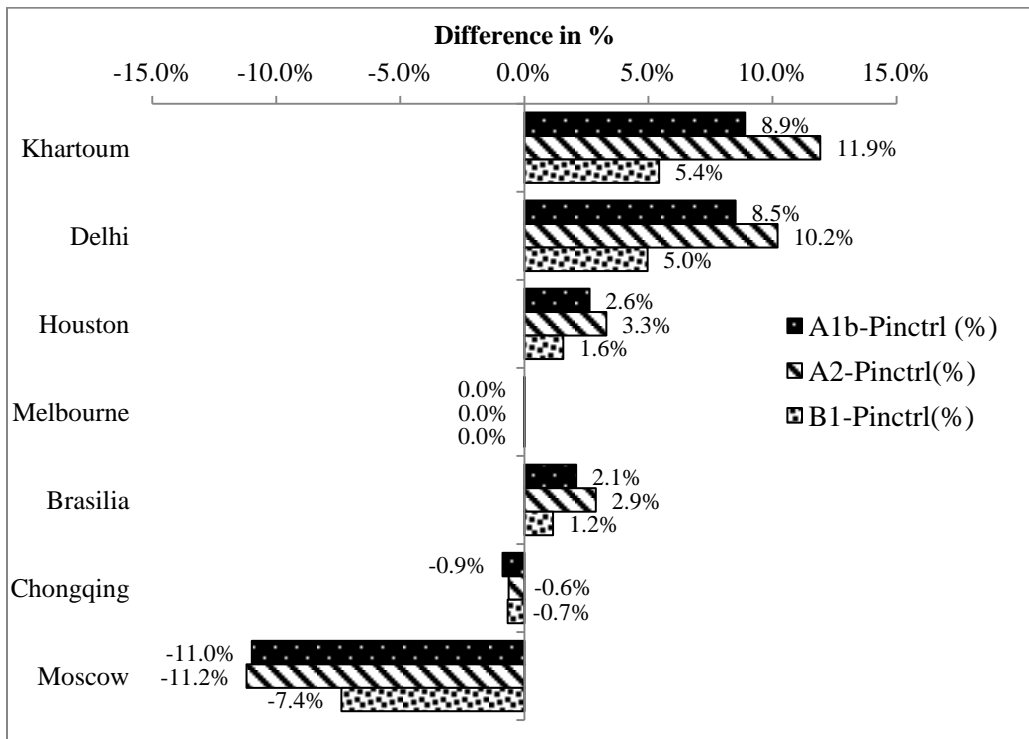


Figure 4- 7. Work Hour Difference in Percentage between Global Warming Scenarios and Pre-industrial Control (Model NOAA CM2.1 2090s' Data)

Global Warming Scenarios vs. Current Scenarios

This section investigates the future global warming effect in comparison to current scenarios. Global GHG emissions due to human activities have been growing since 1850 (Pachauri and Reisinger 2007). The previous section investigated the difference in work hour estimates between three global warming scenarios by 2090s and pre-industrial control. Currently, we have already experienced the times from 1850s through 2000s. It is more of interest to the construction industry to understand the future global warming impact on the current business. The research effort used the climate projection data during the 2090s and the historical data during 2000s for the simulation to obtain the work hours required to build the model project. The authors refer the historical temperature and humidity data from 2000 to 2010 as the current scenarios.

Table 4- 8 and Figure 4- 8 illustrate the comparison of work hours required to build the model project between Model HADCM3's three global warming scenarios and current climate scenarios across the seven cities. The same comparisons were replicated using NOAA CM2.1 model as well. The tabulated and graphed results are shown in Table 4- 9 and Figure 4- 9. Those differences that are not statistically significant at the 95% confidence level are specifically noted. The largest discrepancy as a result of climate model difference was observed on Houston. With the projection data of the HADCM3model, Houston could experience 5.1% to 7.4% increase in the work hours required to build the model project by 2099. As opposed to the case using projections of NOAA CM2.1 model, Houston could experience a change from -0.1 to 1.57% depending on the emission scenario; the results on 2 out to 3 emission scenarios are not statistically significant. Figure 4- 6 and Figure 4- 7 show that the work hours required to build the model project in Khartoum and Delhi increase remarkably under the consideration of global

warming with both climate models compared to the current condition. The increased percentage for Khartoum ranges from 0.3 to 7.7% depending on the emission scenario and model used for simulation while the increased percentage for Delhi ranges from 2.4 to 7.5%. By 2090s, Brasilia could experience minor to moderate increase in the work hour estimates ranging from 1.0 to 4.4%. On average, there are slightly decreases in the work hour estimates observed in Chongqing compared to current condition; however, the results obtained from the NOAA CM2.1 model are not statistically significant. From the simulation results, Melbourne could experience little productivity gain. However, the magnitude of gain is not noticeable, approximately 0.3%. Model HADCM3 and NOAA CM2.1 show the opposite results on Moscow across the three emission scenarios. For HADCM3 model, on average the work hours required to build the model project decrease by 0.1% with A1B scenario, and increase by 2.7% under A2 and 4.5% under B1 scenario, respectively. However, those differences are not statistically significant. Regarding the Model NOAA CM2.1, Moscow could experience productivity gain, ranging from 0.3 to 4.4%; However, the result with emission scenario B1 is not statistically significant at the 95% confidence level.

Table 4- 8. Comparisons between Global Warming Scenarios (Model HADCM3 2090s' Data) and Current Condition

Location	Work Hour			A1b-Current				A2-Current			B1-Current		
	A1b	A2	B1	Current	Diff.	%	Sig.	Diff.	%	Sig.	Diff.	%	Sig.
Khartoum	59,638	61,246	58,007	57,852	1,786	3.1%	0.003	3,394	5.9%	0.001	155	0.3%	0.695 ^a
Delhi	61,167	61,460	60,385	57,600	3,567	6.2%	0.001	3,861	6.7%	0.001	2,786	4.8%	0.005
Houston	60,349	60,456	59,052	56,196	4,153	7.4%	0.001	4,259	7.6%	0.001	2,855	5.1%	0.001
Melbourne	54,338	54,338	54,338	54,504	(166)	-0.3%	0.001	(166)	-0.3%	0.001	(166)	-0.3%	0.001
Brasilia	57,043	56,942	56,359	54,634	2,409	4.4%	0.001	2,308	4.2%	0.001	1,725	3.2%	0.001
Chongqing	55,275	55,221	55,231	55,615	(340)	-0.6%	0.025	(394)	-0.7%	0.014	(384)	-0.7%	0.001
Moscow	60,885	62,595	63,692	60,972	(86)	-0.1%	0.940 ^a	1,623	2.7%	0.272 ^a	2,720	4.5%	0.064 ^a

^a. Result is not statistically significant at the 95% confidence level.

Table 4- 9. Comparisons between Global Warming Scenarios (Model NOAA CM2.1 2090s' Data) and Current Condition

Location	Work Hour			A1b-Current				A2-Current			B1-Current		
	A1b	A2	B1	Current	Diff.	%	Sig.	Diff.	%	Sig.	Diff.	%	Sig.
Khartoum	60,638	62,324	58,709	57,852	2,786	4.8%	0.001	4,473	7.7%	0.001	858	1.5%	0.063
Delhi	60,960	61,908	58,968	57,600	3,361	5.8%	0.001	4,309	7.5%	0.001	1,369	2.4%	0.030
Houston	56,703	57,077	56,122	56,196	507	0.9%	0.103 ^a	881	1.6%	0.010	(75)	-0.1%	0.779 ^a
Melbourne	54,338	54,341	54,338	54,504	(166)	-0.3%	0.001	(163)	-0.3%	0.001	(166)	-0.3%	0.001
Brasilia	55,697	56,129	55,189	54,634	1,063	1.9%	0.001	1,495	2.7%	0.001	555	1.0%	0.001
Chongqing	55,342	55,480	55,456	55,615	(273)	-0.5%	0.065 ^a	(134)	-0.2%	0.309 ^a	(158)	-0.3%	0.297 ^a
Moscow	58,437	58,296	60,807	60,972	(2,535)	-4.2%	0.012	(2,676)	-4.4%	0.014	(165)	-0.3%	0.889 ^a

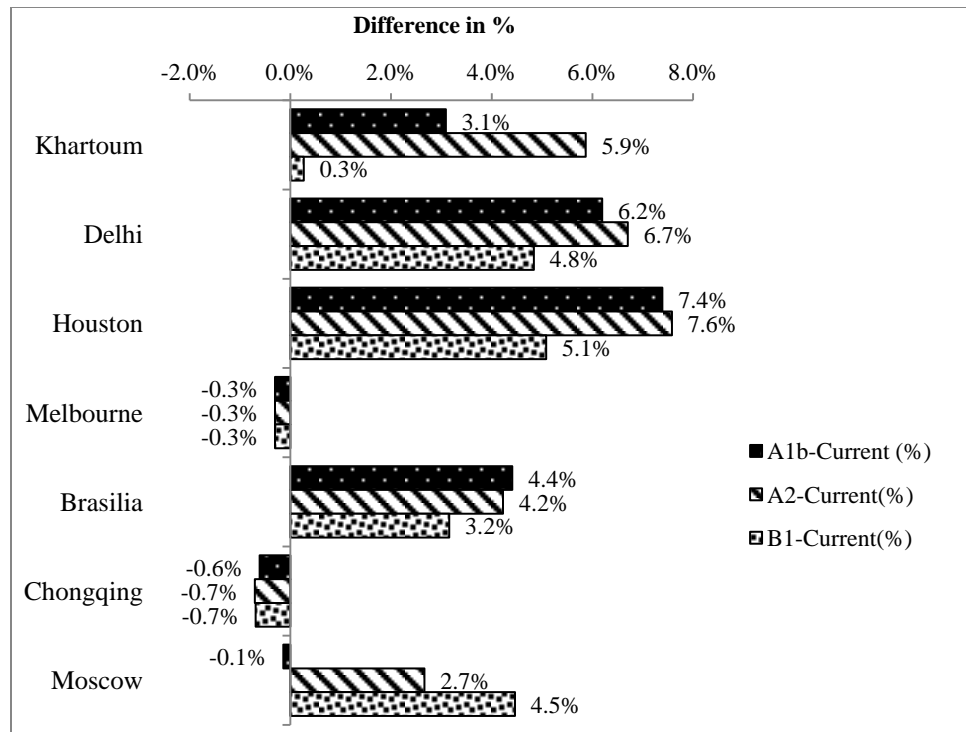


Figure 4- 8. Work Hour Difference in Percentage between Global Warming Scenarios(Model HADCM3 2090s' Data) and Current Condition

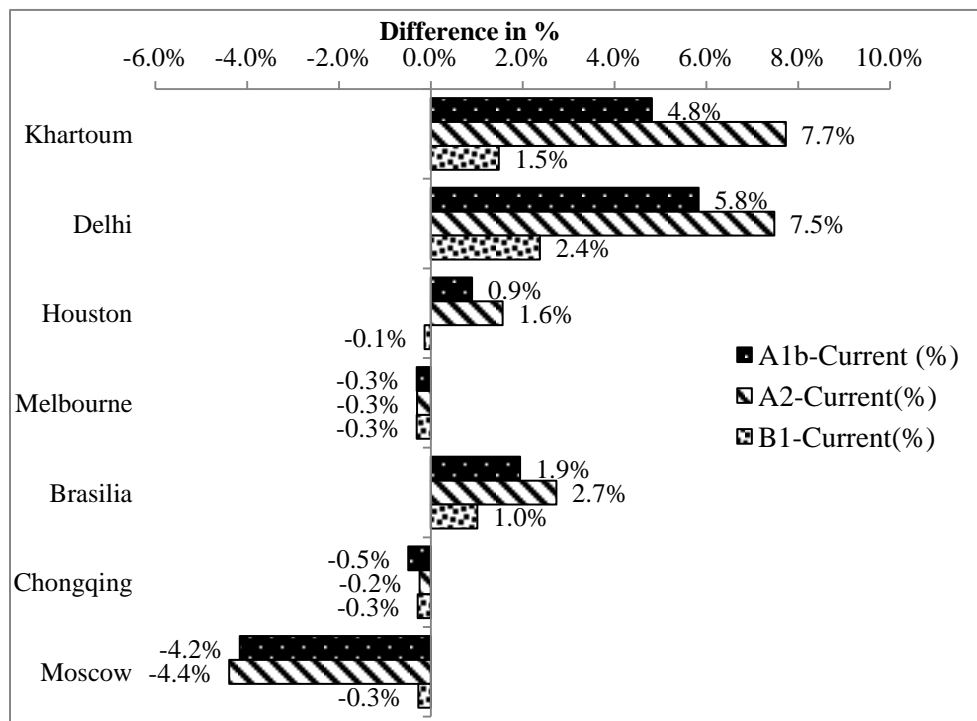


Figure 4- 9. Work Hour Difference in Percentage between Global Warming Scenarios(Model NOAA CM2.1 2090s' Data) and Current Condition

Schedule Performance Visual Comparison

Two 4D animations representing two weather scenarios and illustrated in parallel allows visualization of the difference in schedule performance. This section presents an example of schedule performance comparison of the model project to be built in Khartoum, Sudan under the HADCM3's weather scenarios of A2 and Pre-industrial control, starting on October 1, 2096. The model project is anticipated to be completed on April 22, 2098 with A2 climate projection data, and March 26, 2098 with Pre-industrial Control projection data, which means the project can be completed 27 days earlier without the global warming effect under examination. Figure 4- 10 describes the status of the project progress at various time points under the described emission scenarios with differences being highlighted. The "side-by-side" 4D animation comparison visualizes the impact of the global warming on the model project, and the impact can be easily understood and requires less reader cognitive demand.

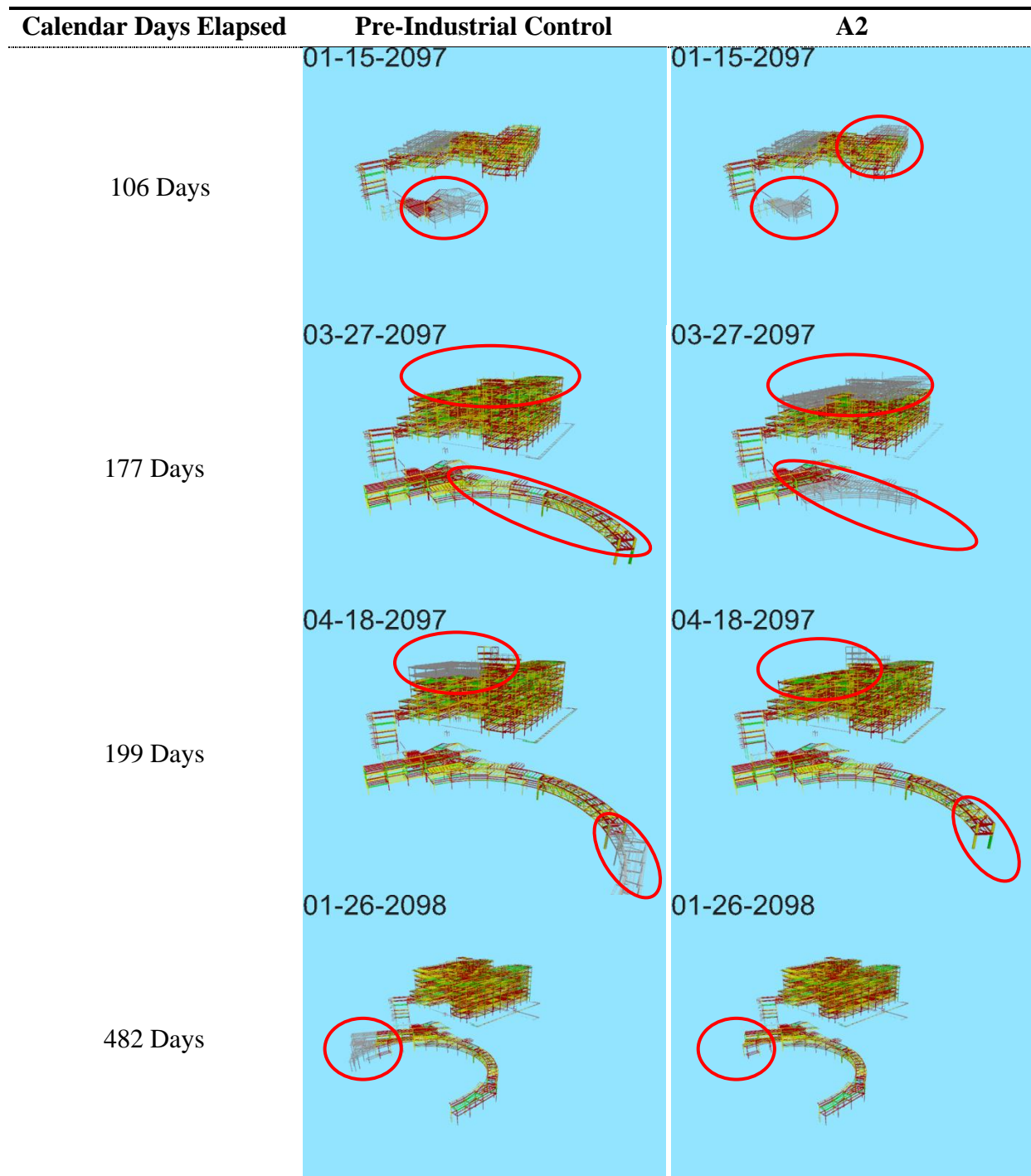


Figure 4- 10. Example of Schedule Performance Comparison Between Pre-Industrial Control and A2 in Khartoum

Note: Gray color represents the work at the beginning stage; color represents the work completed.

DISCUSSION

One of the major contributions of this research is the framework that was used to investigate the potential impact of forecasted global warming trends on construction productivity at various global locations. The major difference of schedule simulation interface between this study and previous research efforts (Benjamin and Greenwald 1973; Lee 2005; Lee and Arditi 2006) is that previous research efforts remain their focus on a high level CPM schedule while the described study reaches to the details of a lower level (crew level) schedule with the assistance of BIM and integrated information of construction productivity. It is also a first kind of research that addresses the schedule impact by simulating the productivity influencing factors at a greater detailed level.

The current climate models collected by CMIP are recognized as coexisting rather than competing models (Knutti et al. 2010; Parker 2006). It is readily acknowledged that current models do produce variations in future projection data with regard to the different variables because of the subtle difference in the model assumptions (Cess et al. 1989; Covey et al. 2003; Mitchell et al. 1989). Currently, there is no single definite model performance metric to determine whether a model is a good or bad fit (Knutti et al. 2010). Rather than relying on the results obtained from a single climate model, this research effort adopted two climate models to demonstrate the argument that differences in climate models may produce significant differences in work hour estimates using the projection data from 2050 to 2099 across the category of GHG emission scenarios under examination. CMIP collected 18 leading climate models from different research centers around the world; multi-model averages have been used in previous research studies (Cantelaube and TERRES 2005; Gillett et al. 2005; Palmer et al. 2005; Thomson et al. 2006), because empirical evidence from the area of numerical modeling argues that a multi-

model average yields more confidence in the predictions than a single model(Knutti et al. 2010). However, Knutti et al.(2010) argues that averaging model output may impair the accuracy of the prediction, and he further states that quantitative methods to aggregate models are still in their preliminary stage. Therefore, it is appropriate for the described research to adopt two models and perform the same analyses; this practice also allows the readers to visualize the possible magnitude of variations in work hour estimates due to climate model difference.

Among the comparisons shown in Table 4-3, most of the differences are statistically significant, except in 4 cases, and the tests were not able to be performed for Melbourne. However, the results that are statistically significant should be interpreted with caution. A statistically significant difference does not necessary mean the magnitude of the difference are really significant to decision makers depending on the context. For instance as shown in Table 4-3, under the emission scenario of A1b the difference of steel work hours estimates between HADCM3 and NOAA CM2.1 models only amounts to 159 work hours, and the results are statistically significant at 99.6% confidence level. Under this circumstance, the difference compared to value of the total work hours is very negligible.

The primary purpose of developing multiple families of GHG emission scenarios was to explore the uncertainties of the potential trends in global climate development and future emissions (Nakicenovic et al. 2000). Though the emission scenarios were developed based on people's choices and global economy structure in the absence of explicit climate policies, they are still considered as the state-of-the-art assessment of GHG emissions because of the thorough literature and collaborative efforts from different climate research centers (Nakicenovic et al. 2000). The three emission scenarios adopted by this paper come from three big families: A1, A2, and B1. For the cities with warmer climate, such as Khartoum, Delhi, Houston, and Brasilia, the

average steel work hour estimates with A1b and A2 emission are consistently larger than the estimates with B1 emission scenario across both climate models (see Figure 4- 4 and Figure 4- 5). The findings are consistent with the "storylines" of the emission scenarios, since Families A1 and A2 are more economy focused while B1 is more environmentally friendly. Therefore, the driving force of global warming under A1 and A2 is greater than B1. Moscow's decreased cold climate would experience the opposite trend. This finding is also quite intuitive, GHG emissions under B1 contribute less to the temperature increase than A1 and A2, which means craft workers are subject to more cold days under B1 and less productive.

The project start date and project location 2-way ANOVA shows the project start date and location do significantly affect the work hour estimates required to build the model project, and the two factors have interactive effects with the work hour estimates. The analyses also allow the companies who potentially conduct business in these regions to have a general knowledge about how the work hours vary from seasonal and regional effects.

GHG emissions due to industrial development are a major cause of global warming. Throughout the course of global warming, human activities, such as construction activities, are affected as well. The authors performed comparisons of work hours required to build the model project using 2090s' project data between global warming scenarios and pre-industrial control. The comparison with pre-industrial control shows the magnitude of productivity loss over the course of industrial development by 2090s. Since we are already in the mist of the global warming, the results of comparisons between 2090s' and current climate scenarios should provide more meaningful insights to the construction practitioners. By and large, the trends are similar. Khartoum and Delhi are anticipated to experience considerable productivity losses, ranging from 0.3 to 7.7%. Houston's results are dependent on the models used: the productivity

loss could amount to 5.1 to 7.6% with HADCM3 model, while the productivity loss is very minimal with NOAA CM2.1 model ranging from -0.1 to 1.6%. The same trend observed on Brasilia that HADCM3 model yields higher work hour estimates than NOAA CM2.1 model. This discrepancy is because HADCM3's projections in temperature and humidity are higher than NOAA CM2.1's for both Houston and Brasilia. Melbourne and Chongqing will be the least impacted with slightly productivity gain. Moscow is anticipated to have productivity gains across three global warming scenarios with NOAA CM2.1 model and have productivity losses under A2 and B1 scenarios with HADCM3 model. To some degree, the findings on Khartoum, Delhi, Brasilia, and Melbourne agrees with the findings identified by Kjellstrom et al (Kjellstrom et al. 2009) though broader regions were the focus of their studies. Regarding the comparisons between 2090s' projections with current weather scenarios, the results derived by two climate models show a significant discrepancy which is caused by the model difference.

Strategies to Accommodate Global Warming

Heat will be a great safety concern in the future for the regions subject to prolonged warm days and elevated temperatures. Not only can heat impose safety threats but also impair productivity. To alleviate complications as a result of global warming, prefabrication, preassembly, modularization & off-site fabrication (PPMOF) can be a measure. PPMOF is carried out in controlled environments, which could greatly reduce the chance of exposure to health and safety and environmental hazards, improve quality, reduce on-site congestion and rework, etc. (Pasquire and Gibb 2002). Though great benefits are manifested in PPMOF, transportation logistics place a great challenge on the feasibility of PPMOF, such as the route accessibility in terms of the size and weight limitation restriction, availability of transportation and lifting equipment (CII 2002).

CONCLUSIONS AND RECOMMENDATIONS

This dissertation research is the first of its kind to specifically examine the global warming effect on construction labor productivity at a project level. The primary contributions of this study to the overall body of knowledge include the following:

- 1) It provides the framework of integrating BIM with a CPM schedule to simulate the impact of forecasted global warming trends on construction productivity at a project level;
- 2) It affords the knowledge of how different emission scenarios would affect construction productivity at a project level;
- 3) It demonstrates how much global warming's impact on construction labor productivity varies in terms of geographical locations; and
- 4) It offers possible strategies that could accommodate the potential adverse impact due to the global warming.

The findings associated with this study is of significant value to both the scientific community and the construction industry. The major findings of this research on global warming by 2099 compared to current weather scenarios can be summarized as follows:

- 1) Work hour estimates required to build a project using forecasted global warming data may vary with the adopted climate models;
- 2) Khartoum and Delhi are anticipated to experience productivity losses ranging from 3.1 to 6.2% under emission scenario A1b, 5.9 to 7.7% under scenario A2, and 0.3 to 4.8% under scenario B1;
- 3) Houston will have a productivity loss ranging from 5.1 to 7.4% across three emission scenarios with HADCM3 model versus 0.1% gain to 1.6% loss with NOAA CM2.1 model;

Brasilia will experience 3.2 to 4.4% productivity losses with HADCM3 model versus 1.0 to 2.7% losses with NOAA CM2.1 model;

4) Melbourne and Chongqing will be the least impacted with less than 0.7% productivity gains.

5) Moscow is anticipated to have productivity gains ranging from 0.3 to 4.4% with NOAA CM2.1 model, and experience productivity losses as much as 2.7 to 4.5% with HADCM3 model .

There are a few limitations with this research study. The work builds upon the existing knowledge about global climate change and the relationship between labor productivity, temperature, and humidity. Therefore, this research is only as good as the existing knowledge. However, it should be noted that models adopted by this research, by no means, nullify the developed framework that was used to predict the impact of anticipated global warming on construction projects. This research effort excludes precipitation in this study; potential impact of climate change may shift the current weather pattern, which could result in more rainfalls in certain area of the world and thus affect project schedule substantially. This study assumed that technology change does not alter iron worker's labor productivity, and adaption to climate change was not taken into account. The focus of this current research on the steel trades is due to the lack of widely accepted model data information standards among the other trades. Future research will include precipitation and wind effects and other trades in the model as the development and implementation of BIM standards in the construction industry matures. Future research will also examine the economic impact of climate change at the regional construction industry level instead of just looking at a project level by encompassing representatives types of construction from other sectors, such as industrial, infrastructure, and residential. Though the

external validity of the research findings might be limited because the data collected are geographical location specific, the validity of the developed framework by this research effort would not be affected at all.

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CHAPTER 5

CONCLUSION

SUMMARY

The main focus of this study was to provide a proof of concept in developing a framework of integrating BIM model with productivity information and a lower level CPM schedule to simulate and analyze the impact of construction productivity influencing factors at a project level. As shown in the conceptual overview of the dissertation (Figure 5- 1), the factors investigated in this dissertation fall into the two main categories, materials and weather, described in Thomas and Skarcan's (1994) factor model. These two categories were not arbitrarily selected. The impact of the steel innovation examined in the study represents a factor with a static impact, which means the productivity impact would not change over the time as the project progresses. Nevertheless, temperature and humidity are one of the representative factors that have a dynamic effect on construction productivity. The complexity level of modeling static factors is also relatively simpler than dynamic factors. In particular, Chapter 2 developed a framework that is capable of intelligently analyzing the productivity impact of a type of steel innovation, steel quick connection systems, in terms of schedule and cost performance. Chapter 3 developed a framework that can simulate the impact of temperature and humidity on a structural steel model project. Chapters 2 and 3 used two sources of unit rate productivity, RSMeans and Richardson, respectively. Since Chapter 2 involved a 5-story office building, the unit rate productivity obtained from RSMeans best matches the building type and number of stories for the examined project. Chapter 3 used the unit rate productivity from the Richardson Construction Estimating Standards, because the descriptions of conditions under which the unit rate productivity was collected best match the conditions for optimal operation efficiency. Chapter 4 utilized the framework built in Chapter 3 and investigated the impact of forecasted global warming trends on a model project on a global scale.

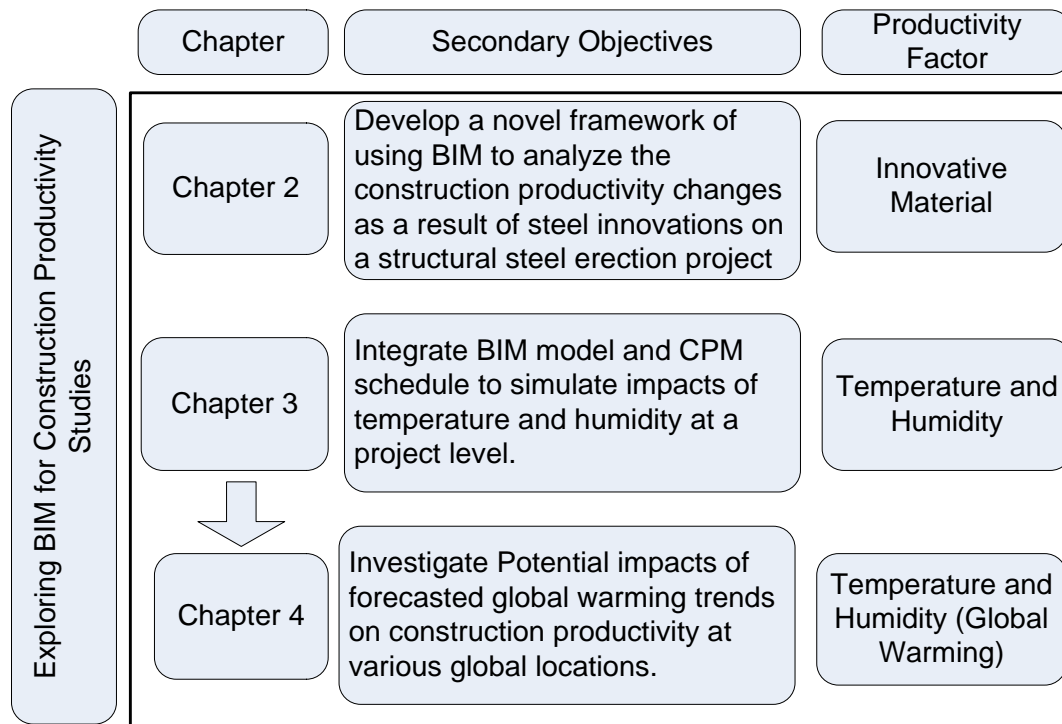


Figure 5- 1. Conceptual Overview of Dissertation

MAIN CONCLUSIONS AND CONTRIBUTIONS TO THEORY AND PRACTICE

This dissertation is a practical and proof- of- concept research. Though this dissertation research only focused on two specific factors under the category of material and weather, the applicability of the developed framework can be generalized to accommodate other factors with the similar nature described in the dissertation. If readers limit the applicability of this research to the examined factors in the dissertation research only, the big picture of this research might be lost. The framework itself and its capability are the essence of this study. There are few "takeaways" for both BIM software developers, construction practitioners, owners, and researchers.

Overall, the concept of the framework could be commercialized by BIM software vendors. Nowadays, since most of the software provides Application Programming

Interface(API), writing add-ons and extensions to customize the program with additional functions beyond its original capability is possible. The software developer can develop an interface that interacts with the BIM and scheduling software.

The developed framework can have a few different uses. First for project owners, this framework can be used at a pre-project planning stage as a guide for decision making on project execution. For instance, if the impact of alternative materials on cost and schedule needs to be assessed on a project, the framework can be used to strategically select the most optimal material that meets owners' needs according to the key drivers of the project. If a factor that is related to geographical locations, the developed framework can be used as an auxiliary tool for project location selection. Second, for a construction company, this framework can be used for schedule optimization if the factor to be modeled changes with time. The framework can be applied both during the pre-construction and the construction stage. Third, the framework can also be used to perform better project estimation. By correctly modeling the factors and analyzing the impact of the factors on cost can improve the accuracy of estimates and minimize surprises in terms of project budgets. Fourth, this framework is a simulation tool. By analyzing the simulation results, associated knowledge against the examined factors can be generated and disseminated within an organization.

The 4D schedule analysis presented in the research show its potential of visualizing the schedule performance due to changes. This method is an alternative to traditional way of presenting results in a tabulated forms or charts. This method is an augmented way of delivering information without stressing too much on audience/readers cognitive capability.

The above contributions are generalized as if the framework is utilized to model other factors besides the factors described in this dissertation. However, the authors selected two specific factors for this dissertation; partially this is because of the accessibility of the data associated with the factors examined. Besides the general contributions of the developed framework, contributions associated with the understanding of two specific factors examined by this dissertation is also not negligible and might concern a group of population in the construction industry.

The main idea of the Chapter 2 was inspired by the CII Research Team RT252's initiative to identify steel innovations in steel trades. Finally, the team agreed upon the investigation of a steel quick connection system developed by ConXtech. Field data were collected through site visits. Activity analyses performed at task level showed that significant productivity improved compared to conventional connection systems. The quest for understanding the impact of the connection system at a project level in terms of schedule performance inspired the authors to develop an intelligent model to analyze the impact of process change. Again, the developed framework is the main contribution of this study. By using the develop framework, the following conclusions can be drawn from the examination of the quick connection system applied on a commercial office building model project:

- 1) The quick connection system could save 43% of the work hours compared to a conventional system on the model project; and
- 2) With quick connection systems, on average more number of piece of steel members can be installed than conventional system, which requires more logistic efforts to keep up the faster erection speed.

Chapter 3 developed a framework that is capable of simulate the impact of temperature and humidity on construction productivity of structural steel erection on a healthcare facility project. Four cities'(Lexington, Newark, Houston, and Long Beach) historical weather data from 1961 to 2010 were used to test the applicability of the develop framework. The statistical analyses of the simulation results generate knowledge that could provide an extra dimension of criteria that could be used during pre-project planning in terms of project location and start date selection. Since the model project is just an instance of a hospital project, every project can be unique to each other. Even if a project is executed in one of the locations examined in this study, the results of chapter 3 might not be directly applied because the project scale might be different than the model project. However, the general conclusions still can be inferred from the analyses:

- 1) The total work hours required to build a project may significantly differ with the location of the project since climate does vary with geographic locations;
- 2) Seasons in which a project is chosen to start may have a significant effect on the total work hours required to build the project when the place where the project is located has a distinct seasonal change; and
- 3) Project start date and project location have interactive effect on the total work hours required to build a project.

The developed framework may greatly benefits the entities who standardize their design and operate business across regions that are geographically far apart and have different climate patterns. The framework can help them optimize the construction costs of a portfolio of projects by selecting the best location and project start date.

Chapter 4 is an extension of Chapter 3 by utilizing the framework built in Chapter 3 to investigate the potential productivity impact of forecasted global warming trends generated by

the leading climate models considering the different GHG emission scenarios. This chapter also presents an example of how the model can be used. As a good practice, Chapter 4 examined the 6 international and 1 domestic cities. Six international cities also include the major cities from BRIC countries where economy development are anticipated to experience with the greatest scale in the near future. Among the cities examined in Chapter 4, the major findings are as follows:

- 1) Work hour estimates required to build a project may vary significantly with the climate model and emission scenarios used for the study;
- 2) Khartoum and Delhi are expected to experience considerable productivity losses as many as 7.5%;
- 3) Houston and Brasilia are anticipated to have productivity losses as many as 7.6% and 4.4%, respectively, depending on climate model and GHG emission scenarios;
- 4) Melbourne and Chongqing are least impacted with possible slightly gains; and
- 5) Moscow has significant productivity gains compared to pre-industrial gas emission level. However, comparing to current climate scenarios, Moscow might experience productivity gains or losses depending on the selected climate model projections.

With the framework used in Chapter 4, a construction company can examine the impact of global warming trends on any locations that are interested. However, the results presented in Chapter 4 are still relevant to those companies that already have or plan to expand their business in these locations. The numbers shown in the statistical analyses do not necessarily mean the exact productivity losses or gains a company would experience; at least, they provide a ball park figure within the context of the model project provided.

As a contribution to the academic field, Chapter 4 has confirmed that climate model differences can yield significantly different productivity impact estimates as a result of global warming. To study the impact of global warming on various sectors, climate models serve a basis on which the estimates of impact are made. This research once again has raised the climate research community's awareness that there is an urgent need for a diagnosis and understanding of the causes of model differences in order to obtain a meaningful and accurate estimate.

SUGGESTIONS FOR FUTURE RESEARCH

The simulation tool developed in this dissertation is a deterministic simulation tool without the degree of randomness. However, variability is often inherent to a system or model. In this research, the author used the productivity data from the Richardson's database as baseline productivity. The variability associated with the productivity data was not considered. In this case, a stochastic simulation would be more preferable. A stochastic simulation accounts for the source of randomness in a model, which better captures the behavior of the model (Ripley 2009). Future research could consider variability associated with the variables of the model and incorporate stochastic simulation into the framework.

The current model project used in the research only focuses on structural steel due to the limitations of current BIM standards as well as limited data standards implementations by the BIM software vendors. As the BIM standards mature and the wide adoption by software vendors, other trades can be included in the scope of the future research studies. Future research can develop two complete prototypical models: one for healthcare facility and the other one for industrial petrochemical refinery plant that encompass the major components of each type of

project. The developed model can be used for benchmarking studies in the areas of productivity measurement, labor utilization strategies, new construction methods assessment, etc.

This dissertation research focused on two specific factors related to material and weather and examined the factor independently. In reality, multiple factors could act jointly and/or interactively on a project. Factors can have either static or dynamic effects as described earlier. Overtime has been identified as one of the factors that compromise productivity by various research efforts (Brunies and Emir 2001; Hanna et al. 2005; National Electrical Contractors Association 1989); and the studies show that productivity negatively correlates to work hours and length of extended over time(in weeks). Future studies can attempt to model two dynamic factors by incorporate overtime and temperature and humidity in the model.

Another direction of expansion of the dissertation research can incorporate spatial elements in the model. Overcrowding due to large crew size or interference with other trades at the jobsite can be a factor that decreases productivity (Hanna and Heale 1994; Mattila 2007). Future research can integrate a BIM model with a manpower resource loaded CPM schedule to simulate the productivity impact of the dynamic change of the craft density on the jobsite at a project level. BIM is a great tool for spatial visualization. This proposed framework allows more comprehensive project level analyses and better workforce planning, in order to achieve the best productivity and lowest project costs.

Finally, the concept of this research can also be applied to civil/infrastructure projects. Currently, the development of virtual design and construction (VDC) for civil projects is well behind building sectors (Drogemuller 2009). However, as more research efforts invested in this area, capability and interoperability of software, the software vendors will make rapid

improvement(Drogemuller 2009). Future research can include civil/infrastructure projects and modify the framework of the dissertation to fit the needs for civil/infrastructure settings.

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APPENDIX

Appendix I VBA Code for Weather Data Download and Import Interface

Option Explicit

'Function add Location to the combobox

Private Function addLocal(comboName As combobox) As Variant

 comboName.Clear

 With comboName

 .AddItem "Lexington"

 .AddItem "Newark"

 .AddItem "Houston"

 .AddItem "Long Beach"

 End With

End Function

'Function add Month to the combobox

Private Function AddMonth(comboName As combobox) As Variant

 comboName.Clear

 With comboName

 .AddItem "January"

 .AddItem "February"

 .AddItem "March"

 .AddItem "April"

 .AddItem "May"

 .AddItem "June"

 .AddItem "July"

 .AddItem "August"

 .AddItem "September"

 .AddItem "October"

 .AddItem "November"

 .AddItem "December"

 End With

End Function

'Add February 29 Days to the ComboBox

Private Function AddFeb29Days(comboName As combobox) As Variant

```

    comboName.Clear
    Dim i As Integer

    For i = 1 To 29 Step 1
        comboName.AddItem (i)
    Next

End Function
'Add Days of the months (called it large Month hereby) with 31 days to the ComboBox
Private Function Add31Days(comboName As combobox) As Variant

    comboName.Clear
    Dim i As Integer

    For i = 1 To 31 Step 1
        comboName.AddItem (i)
    Next

End Function

'Add Days of the months (called it small Month hereby) with 30 days to the ComboBox
Private Function Add30Days(comboName As combobox) As Variant

    comboName.Clear
    Dim i As Integer

    For i = 1 To 30 Step 1
        comboName.AddItem (i)
    Next

End Function

'Function that is designed to add years to the combobox
Private Function AddYear(comboName As combobox) As Variant

    'i is used to count the loop
    Dim i As Integer
    Const Years As Integer = 52

    'start out from current years and date back to
    'number of years by minus 1 in each loop

    For i = Year(Date) To Year(Date) - 52 Step -1

```

```

        'add the year to combobox
        comboName.AddItem (i)

    Next

End Function
Private Sub btnDownload_Click()
    Dim myStartingDate As Date
    Dim myEndDate As Date

    myStartingDate = CDate(CStr(ComboFrmMonth.Value) & " " & CStr(ComboFrmDate.Value) _
        & "," & " " & CStr(ComboFrmYear.Value))
    myEndDate = CDate(CStr(ComboToMonth.Value) & " " & CStr(ComboToDate.Value) _
        & "," & " " & CStr(ComboToYear.Value))
    Dim response As VbMsgBoxResult
    If ComboFrmMonth.Value = "" Or ComboFrmDate.Value = "" _
        Or ComboFrmYear.Value = "" Or ComboToMonth.Value = "" _
        Or ComboToDate.Value = "" Or ComboToYear.Value = "" Then
        response = msgbox("Date field cannot be empty!", vbOKOnly, "Warning")

    ElseIf myStartingDate > myEndDate Then

        response = msgbox("End date cannot be earlier than start date!" _
            , vbOKOnly, "Warning")

    Else
        DownloadWeather 'call DownloadWeather() procedure

        On Error GoTo 0

    End If

End Sub
Public Sub DownloadWeather()

    Dim FileName As String
    Dim folderPath As String
    Dim FSO As Object
    Dim ieApp As Object
    Dim Txt As String
    Dim TxtFile As Object

    'The string can be changed according to needs

```



```

Dim URL As String
Dim i As Integer 'use it as loop counter for days
Dim i2 As Integer
Dim DayCounter As Integer
Dim j As Integer 'use it as loop counter for years
Dim DateCounter As Date
Dim txtYear As String
Dim txtMonthDate As String
Dim txtYearMonthDate As String
Dim myYear As String
Dim intMyYear As Integer
Dim StrDate As String
Dim myStartingDate As Date
Dim myEndDate As Date
Dim theTargetPath As String

'Folder path is the directory used to store the weather data
folderPath = BrowseForFolder 'set folder path to the browsed Folder

If folderPath = "" Then
    Exit Sub

Else

    'set the starting Date

    myStartingDate = CDate(CStr(ComboFrmMonth.Value) & " " & CStr(ComboFrmDate.Value) _
        & "," & " " & CStr(ComboFrmYear.Value))
    myEndDate = CDate(CStr(ComboToMonth.Value) & " " & CStr(ComboToDate.Value) _
        & "," & " " & CStr(ComboToYear.Value))

    'set the date format to d/m/yyyy fomart
    DateCounter = Format(CDate(myStartingDate), "mm / dd / yyyy")

    'Retain the year of the Date as type of string
    myYear = Right(myStartingDate, 4)

    'Conver the string into integer
    intMyYear = CInt(myYear)

    i2 = myEndDate - myStartingDate + 1

```

For i = 1 To i2

```
StrDate = CStr(DateCounter)
txtYear = Right(CStr(DateCounter), 4)
txtMonthDate = Left(CStr(DateCounter), Len(CStr(DateCounter)) - 5)
StrDate = Trim(txtYear) & "/" & Trim(txtMonthDate)
```

'URL is changed according to the city selected

'URL can be added according to own needs

Select Case comboLocal.Value

Case "Newark"

```
URL = "http://www.wunderground.com/history/airport/KEWR/" & StrDate &
"/DailyHistory.html?req_city=Newark&req_state=NJ&req_statename=New+Jersey&format=1"
```

Case "Lexington"

```
URL = "http://www.wunderground.com/history/airport/KLEX/" & StrDate &
"/DailyHistory.html?req_city=Lexington&req_state=KY&req_statename=Kentucky&theprefset=SHOW
METAR&theprefvalue=1&format=1"
```

Case "Long Beach"

```
URL = "http://www.wunderground.com/history/airport/KLGB/" & StrDate &
"/DailyHistory.html?req_city=Long+Beach&req_state=CA&req_statename=California&format=1"
```

Case "Houston"

```
URL = "http://www.wunderground.com/history/airport/KHOU/" & StrDate &
"/DailyHistory.html?req_city=Houston&req_state=TX&req_statename=Texas&format=1"
```

Case "Los Angeles"

```
URL = "http://www.wunderground.com/history/airport/KCQT/" & StrDate &
"/DailyHistory.html?req_city=Los+Angeles&req_state=CA&req_statename=California&format=1"
```

End Select

'the folder path that is used to store the weather data

'put the same years' weather data into the same folder

theTargetPath = folderPath & "\" & txtYear

'Create a folder that is not present

If Dir(theTargetPath, vbDirectory) = "" Then 'see if it exists

MkDir (theTargetPath) 'if not make one

End If

FileName = theTargetPath & "\" & Replace(StrDate, "/", "-") & ".txt"

```

Set FSO = CreateObject("Scripting.FileSystemObject")
Set TxtFile = FSO.OpenTextFile(Filename, 2, True, -1)

Set ieApp = CreateObject("InternetExplorer.Application")
ieApp.Visible = True
ieApp.Navigate URL

While ieApp.Busy Or ieApp.ReadyState <> 4
    DoEvents
Wend

Txt = ieApp.Document.body.innerText
TxtFile.Write Txt
TxtFile.Close

ieApp.Quit

Set ieApp = Nothing
Set FSO = Nothing

'add date interval
DateCounter = DateAdd("d", 1, DateCounter)

Next i

End If
End Sub

Private Sub ComboFrmMonth_Change()
    'using proper functions to add days of the corresponding
    'months
    Dim cm29 As Variant 'will be assigned to add 29 days
    Dim cm30 As Variant 'will be assigned to add 30 days
    Dim cm31 As Variant 'will be assigned to add 31 days

    ComboFrmDate.Enabled = True
    Select Case ComboFrmMonth.Value
        Case "January", "March", "May", "July", "August", _
            "October", "December"
            cm31 = Add31Days(ComboFrmDate)
        Case "February"

```

```

        cm29 = AddFeb29Days(ComboFrmDate)
    Case Else
        cm30 = Add30Days(ComboFrmDate)

End Select

End Sub

Private Sub ComboToMonth_Change()
    'using proper functions to add days of the corresponding
    'months
    Dim cm29 As Variant 'will be assigned to add 29 days
    Dim cm30 As Variant 'will be assigned to add 30 days
    Dim cm31 As Variant ' will be assigned to add 31 days

    ComboToDate.Enabled = True
    Select Case ComboToMonth.Value
        Case "January", "March", "May", "July", "August", _
            "October", "December"
            cm31 = Add31Days(ComboToDate)
        Case "February"
            cm29 = AddFeb29Days(ComboToDate)
        Case Else
            cm30 = Add30Days(ComboToDate)

    End Select

End Sub

Private Sub comboLocal_GotFocus()
    'add Locations to the droplist labeled with "Location"

    Dim cm As Variant

    cm = addLocal(comboLocal)

End Sub

Private Sub ComboFrmMonth_GotFocus()
    'add months to the droplist labeled with "From"

    Dim cm As Variant

```

```

    cm = AddMonth(ComboFrmMonth)

End Sub
Private Sub ComboToMonth_GotFocus()
'add months to the droplist labeled with "From"

    Dim cm As Variant

    cm = AddMonth(ComboToMonth)

End Sub

'add Years to the combobox
Private Sub ComboFrmYear_Gotfocus()
    Dim cmFrmYear As Variant
    'Clear the contents in the droplist
    ComboFrmYear.Clear
    cmFrmYear = AddYear(ComboFrmYear)

End Sub

'add years to the Combobox
Private Sub ComboToYear_GotFocus()
    Dim cmToYear As Variant
    'Clear the contents in the droplist
    ComboToYear.Clear

    cmToYear = AddYear(ComboToYear)

End Sub
'Evaluate the date if Feb 29th is a valid value for that year
'when moving away the cursor
Private Sub ComboFrmYear_LostFocus()

    PopFrmDateMsgBox

End Sub
Private Sub ComboFrmDate_GotFocus()
    Dim cm29 As Variant 'will be assigned to add 29 days
    Dim cm30 As Variant 'will be assigned to add 30 days
    Dim cm31 As Variant ' will be assigned to add 31 days

```

```

Select Case ComboFrmMonth.Value
    Case "January", "March", "May", "July", "August", _
        "October", "December"
        cm31 = Add31Days(ComboFrmDate)
    Case "February"
        cm29 = AddFeb29Days(ComboFrmDate)
    Case Else
        cm30 = Add30Days(ComboFrmDate)

```

```

End Select

```

```

End Sub

```

```

Private Sub ComboToDate_GotFocus()
    Dim cm29 As Variant 'will be assigned to add 29 days
    Dim cm30 As Variant 'will be assigned to add 30 days
    Dim cm31 As Variant ' will be assigned to add 31 days

```

```

Select Case ComboToMonth.Value
    Case "January", "March", "May", "July", "August", _
        "October", "December"
        cm31 = Add31Days(ComboToDate)
    Case "February"
        cm29 = AddFeb29Days(ComboToDate)
    Case Else
        cm30 = Add30Days(ComboToDate)

```

```

End Select

```

```

End Sub

```

```

'Evaluate the date if Feb 29th is a valid value for that year
'when moving away the cursor
Private Sub ComboFrmDate_LostFocus()

```

```

    PopFrmDateMsgBox

```

```

End Sub

```

```

'Evaluate the date if Feb 29th is a valid value for that year
'when moving away the cursor
Private Sub ComboFrmMonth_LostFocus()

```

```

    PopFrmDateMsgBox

```

End Sub

'Evaluate the date if Feb 29th is a valid value for that year

'when moving away the cursor

Private Sub ComboToYear_LostFocus()

 PopToDateMsgBox

End Sub

'Evaluate the date if Feb 29th is a valid value for that year

'when moving away the cursor

Private Sub ComboToDate_LostFocus()

 PopToDateMsgBox

End Sub

'Evaluate the date if Feb 29th is a valid value for that year

'when moving away the cursor

Private Sub ComboToMonth_LostFocus()

 PopToDateMsgBox

End Sub

'Procedure to evaluate the date if Feb 29th is a valid value for

' the selected year "Followed by From"

Sub PopFrmDateMsgBox()

 Dim msgrs As VbMsgBoxResult

 If ComboFrmYear.Value = "" Then

 msgrs = msgbox("The date has missed something.", vbOKOnly, "Warning")

 ElseIf ComboFrmMonth.Value = "February" And ComboFrmDate.Value = _

 29 And ComboFrmYear.Value Mod 4 <> 0 Then

 msgrs = msgbox("Your date should be slected between 1-28", vbOKOnly, "Warning")

 End If

End Sub

'Procedure to evaluate the date if Feb 29th is a valid value for

' the selected year "Followed by To"

```

Sub PopToDateMsgBox()
    Dim msgrs As VbMsgBoxResult
    If ComboToYear.Value = "" Then
        msgrs = msgbox("The date has missed something", vbOKOnly, "Warning")
    ElseIf ComboToMonth.Value = "February" And ComboToDate.Value = 29 _
        And ComboToYear.Value Mod 4 <> 0 Then
        msgrs = msgbox("Your date should be slected between 1-28", vbOKOnly, "Warning")

```

```

    End If
End Sub

```

'Click Borwse button to browse the folder where weather data folder
'is located

```

Private Sub BtnBrowse_Click()
    Dim FolderDr As Variant
    'CallBrowse folder function
    txtDirectory.Text = BrowseForFolder(FolderDr)

```

```

End Sub

```

```

Function BrowseForFolder(Optional openat As Variant) As Variant
    'Function purpose: To Browser for a user selected folder.
    'If the "OpenAt" path is provided, open the browser at that directory
    'NOTE: If invalid, it will open at the Desktop level

```

```

    Dim ShellApp As Object

```

```

    'Create a file browser window at the default folder
    Set ShellApp = CreateObject("Shell.Application"). _
    BrowseForFolder(0, "Please choose a folder", 0, openat)

```

```

    'Set the folder to that selected. (On error in case cancelled)
    On Error Resume Next
    BrowseForFolder = ShellApp.self.Path

```

```

    On Error GoTo 0

```

```

    'Destroy the Shell Application
    Set ShellApp = Nothing

```



```

'Check for invalid or non-entries and send to the Invalid error
handler if found
'Valid selections can begin L: (where L is a letter) or
'\\ (as in \\servername\sharename. All others are invalid
Select Case Mid(BrowseForFolder, 2, 1)
Case Is = ":"
    If Left(BrowseForFolder, 1) = ":" Then GoTo Invalid
Case Is = "\"
    If Not Left(BrowseForFolder, 1) = "\" Then GoTo Invalid
Case Else
    GoTo Invalid
End Select

```

Exit Function

Invalid:

```

'If it was determined that the selection was invalid, set to False
BrowseForFolder = False

```

End Function

Private Sub btnImport_Click()

Dim directory As String

Dim file As String

Dim sheetName As String

Dim msgResponse As VbMsgBoxResult

Dim osheet As Worksheet

Dim i As Integer

Dim lstRow As Integer

Dim DestCell As String

Dim txtStartRow As Integer

If txtDirectory.Text = "False" Then

```

    msgResponse = msgbox("The directory is invalid!", vbOKOnly, "Warning")

```

Else

```

    directory = txtDirectory.Text & "\"

```

```

    file = Dir(directory, 4)

```

```

sheetName = Left(file, 4)

'see if the name of the worksheet that is going to be created is the same
'as the ones that are already created
For Each osheet In ActiveWorkbook.Worksheets

    If osheet.Name = sheetName Then

        msgResponse = msgbox("There is an exisiting worksheet named the same name as the
worksheet you want to create. Please delete or rename your exiting one ", _
vbOKOnly, "Warning")

        Exit Sub

    End If

Next

ActiveWorkbook.Worksheets.Add

ActiveSheet.Name = sheetName

i = 0

Do While file <> ""

    i = i + 1

    lstRow = ActiveSheet.UsedRange.Rows.Count

    'when i=1 one, paste from Cell A1
    'ohterwise, paste from the end of the spreddsheets
    If i = 1 Then
        DestCell = Trim("A" & CStr(lstRow))
    Else
        DestCell = Trim("A" & CStr(lstRow + 1))
    End If

```

```

'Read the first txt file from row1
'after that just read from the second line
If i = 1 Then
    txtStartRow = 1
Else
    txtStartRow = 2
End If

Sheets(sheetName).Select

With ActiveSheet.QueryTables.Add(Connection:="TEXT;" & directory & file, _
Destination:=Sheets(sheetName).Range(DestCell))
    .Name = "04"
    .FieldNames = True
    .RowNumbers = False
    .FillAdjacentFormulas = False
    .PreserveFormatting = True
    .RefreshOnFileOpen = False
    .RefreshStyle = xlInsertDeleteCells
    .SavePassword = False
    .SaveData = True
    .AdjustColumnWidth = True
    .RefreshPeriod = 0
    .TextFilePromptOnRefresh = False
    .TextFilePlatform = 936
    .TextFileStartRow = txtStartRow
    .TextFileParseType = xlDelimited
    .TextFileTextQualifier = xlTextQualifierDoubleQuote
    .TextFileConsecutiveDelimiter = False
    .TextFileTabDelimiter = False
    .TextFileSemicolonDelimiter = False
    .TextFileCommaDelimiter = True
    .TextFileSpaceDelimiter = False
    .TextFileColumnDataTypes = Array(1)
    .TextFileTrailingMinusNumbers = True
    .Refresh BackgroundQuery:=False
End With
file = Dir()
Loop
End If
End Sub

```

Appendix II VBA Code for Productivity Factor(PF) Calculation

Step 1: Calculate PF for each time point of a day

Option Explicit

Sub CalculatePF()

```
Dim Response As VbMsgBoxResult
Response = MsgBox("Do you want to Continue Computing the Productivity Factor?", _
    vbQuestion + vbYesNo)
If Response = vbNo Then Exit Sub

ActiveSheet.Select 'Sheets Name can be renamed
Dim tempCol As Long
Dim humCol As Long
tempCol = returnCol("Temp")
humCol = returnCol("Hum")

Dim i As Integer
For i = 2 To ActiveSheet.UsedRange.rows.Count
    Dim targetTemp As Single
    Dim targetHum As Single
    targetTemp = Cells(i, tempCol).Value
    targetHum = Cells(i, humCol).Value

    Dim tempRange() As Long
    Dim humRange() As Long
    tempRange = returnRowRange(targetTemp)
    humRange = returnColRange(targetHum)

    Dim tempLbound As Single
    Dim tempUbound As Single
    tempLbound = Sheets("TempHumPF").Cells(tempRange(0), "A")
    tempUbound = Sheets("TempHumPF").Cells(tempRange(1), "A")
    'This statemtn is to deal with when the temperature
    'value is reached the lower bound (-20)
    If tempLbound = tempUbound Then tempLbound = 0

    Dim humLbound As Single
    Dim humUbound As Single
    humLbound = Sheets("TempHumPF").Cells(2, humRange(0))
    humUbound = Sheets("TempHumPF").Cells(2, humRange(1))
```

```

' This statemtn is to deal with when the Humdidity
'value is reached the lower bound
If humLbound = humUbound Then humLbound = 0

Dim PFTemplVsHuml As Single 'A varaible for Productivity Factor
Dim PFTempuVsHuml As Single 'A varaible for Productivity Factor
PFTemplVsHuml = Sheets("TempHumPF").Cells(tempRange(0), humRange(0))
PFTempuVsHuml = Sheets("TempHumPF").Cells(tempRange(1), humRange(0))

Dim PFtargetTempvsHuml As Single
'Use interpolation to get productivity factor under target tempearture
'and lower bound humidity (5%) condition
PFtargetTempvsHuml = PFTemplVsHuml + (PFTempuVsHuml - PFTemplVsHuml) / (tempUbound
- tempLbound) _
    * (targetTemp - tempLbound)

Dim PFTemplVsHumu As Single
Dim PFTempuVsHumu As Single
PFTemplVsHumu = Sheets("TempHumPF").Cells(tempRange(0), humRange(1))
PFTempuVsHumu = Sheets("TempHumPF").Cells(tempRange(1), humRange(1))

Dim PFtargetTempvsHumu As Single
'Use interpolation to get productivity factor under target tempearture
'with upper bound humidity condition
PFtargetTempvsHumu = PFTemplVsHumu + (PFTempuVsHumu - PFTemplVsHumu) /
(tempUbound - tempLbound) _
    * (targetTemp - tempLbound)

Dim PFtargeTempvsHum As Single

PFtargeTempvsHum = PFtargetTempvsHuml + (PFtargetTempvsHumu - PFtargetTempvsHuml) _
    / (humUbound - humLbound) * (targetHum - humLbound)

Cells(i, returnCol("Productivity Factor")) = PFtargeTempvsHum

On Error Resume Next

Next i
End Sub

```

'This procedure is used to find a particular text in a range and return its column position

```
Public Function returnCol(FindText As String) As Long
```

```
    Dim s As Variant
```

```
    'This section finds where the needed column is located at.
```

```
    Set s = Cells.Find(What:=FindText, LookAt:=xlPart)
```

```
    returnCol = s.Column
```

```
End Function
```

'This Function is used to find the Range that a tempearture lookup belongs to

'This Function will return the Row numbers of that range.

```
Function returnRowRange(tempValue As Single) As Long()
```

```
    Dim iRow As Integer ' row number
```

```
    Dim returnRange() As Long
```

```
    Dim compareTempValue As Single
```

```
    iRow = 2
```

```
    Do
```

```
        iRow = iRow + 1 'inital row number which is the row that data begins
```

```
        compareTempValue = Sheets("TempHumPF").Cells(iRow, "A").Value
```

```
    Loop Until tempValue <= compareTempValue
```

```
    ReDim RowRange(2) As Long
```

```
    RowRange(0) = iRow - 1
```

```
    'This "if statement" is to deal with when the temperature
```

```
    'value is reached the lower bound (-20)in TempHumPF table
```

```
    If RowRange(0) = 2 Then RowRange(0) = 3
```

```
    RowRange(1) = iRow
```

```
    returnRowRange = RowRange
```

```
End Function
```

'This Function is used to find the Range that a tempearture lookup belongs to

'This Function will return the Row numbers of that range.

```
Function returnColRange(humValue As Single) As Long()
```

```
    Dim iCol As Integer 'Column number counter
```

```
    Dim colRange() As Long
```

```

' The variable denotes the tempearture value that is the "TempHumPF" table
Dim compareHumValue As Single
    iCol = 1

Do
    iCol = iCol + 1 'inital Col number which is the row that data begins

    compareHumValue = Sheets("TempHumPF").Cells(2, iCol).Value
Loop Until humValue <= compareHumValue

ReDim colRange(2) As Long
colRange(0) = iCol - 1
'This "if statemtn" is to deal with when the Humdidity
'value is reached the lower bound (5%)in TempHumPF table
If colRange(0) = 1 Then colRange(0) = 2
colRange(1) = iCol
returnColRange = colRange

End Function

```

Step 2: Calculate PF Mean for Each Time Interval of a Day

Option Explicit

'This procedure is used to interpolate the the mid-point of the two productivity

'factor points

Sub PFInterpolation()

Dim returnRowArray() As Long

returnRowArray = returnRows() 'call function returnRows that is defined above

Dim i As Integer

For i = 1 To 366

 Dim rowNo As Long

 rowNo = returnRowArray(i)

 If i = 1 Then

 Dim j As Integer

 j = 2

 Do

 Dim mean As Single

 Dim PFCol As Long

 PFCol = returnCol("Productivity Factor")

 Dim PFinterCol As Long

 PFinterCol = returnCol("Productivity Interpolation")

 mean = (Cells(j, PFCol).Value + Cells(j + 1, PFCol).Value) / 2

 Cells(j + 1, PFinterCol) = mean

 j = j + 1

 If j = rowNo Then Cells(j, PFinterCol) = ""

 Loop Until Cells(j, PFCol) = ""

 ElseIf i <> 1 Then

 j = returnRowArray(i - 1) + 1

 Do

 PFCol = returnCol("Productivity Factor")

 PFinterCol = returnCol("Productivity Interpolation")

 mean = (Cells(j, PFCol) + Cells(j + 1, PFCol)) / 2

 Cells(j + 1, PFinterCol) = mean

 j = j + 1

 If j = rowNo Then Cells(j, PFinterCol) = ""

 Loop Until Cells(j, PFCol) = ""

End If

Next i

End Sub

'This procedure is used to calculate the time difference between two time points

Sub timeIntervalCal()

Dim returnRowArray() As Long

returnRowArray = returnRows() 'call function returnRows that is defined above

Dim i As Integer

For i = 1 To 366

 Dim rowNo As Long

 rowNo = returnRowArray(i)

 If i = 1 Then

 Dim j As Integer

 j = 2

 Do

 Dim diff As Single

 Dim TimeCol As Long

 TimeCol = returnCol("Time")

 Dim TimeInterCol As Long

 TimeInterCol = returnCol("Time Interval")

 diff = Cells(j + 1, TimeCol) - Cells(j, TimeCol)

 Cells(j + 1, TimeInterCol) = diff

 j = j + 1

 If j = rowNo Then Cells(j, TimeInterCol) = ""

 Loop Until Cells(j, TimeCol) = ""

 ElseIf i <> 1 Then

 j = returnRowArray(i - 1) + 1

 Do

 TimeCol = returnCol("Time")

 TimeInterCol = returnCol("Time Interval")

 diff = Cells(j + 1, TimeCol) - Cells(j, TimeCol)

 Cells(j + 1, TimeInterCol) = diff

 j = j + 1

 If j = rowNo Then Cells(j, TimeInterCol) = ""

 Loop Until Cells(j, TimeCol) = ""

 End If

Next i

End Sub

'This procedure is used to find a particular text in a range and return its column position

Public Function returnCol(FindText As String) As Long

Dim s As Variant

'This section finds where the needed column is located at.

Set s = Cells.Find(What:=FindText, LookAt:=xlPart)

returnCol = s.Column

End Function

Step3 Using Weight Average to Calculate the Daily Average PF

Option Explicit

'This function is used to find rows containing certain text, and return an array of these row positions

```
Function returnRows() As Long()
```

```
    Dim s As Variant, s2 As Variant
```

```
    Dim returnRow As Long
```

```
    Dim FindText As String
```

```
        FindText = "Average"
```

```
'Dim returnRowArray() As Long
```

'This section finds where the needed column is located at.

```
Set s = Cells.Find(What:=FindText, LookAt:=xlPart, MatchCase:=False)
```

```
Dim i As Integer
```

```
Dim rows() As Long
```

```
i = 1
```

```
returnRow = s.row
```

```
ReDim rows(366) As Long
```

```
rows(i) = returnRow
```

```
Do
```

```
    If i = 1 Then s.Activate Else s2.Activate
```

```
    Set s2 = Cells.FindNext(After:=ActiveCell)
```

```
    returnRow = s2.row
```

```
    i = i + 1
```

```
    rows(i) = returnRow
```

```
Loop Until i = 366
```

```
returnRows = rows
```

```
End Function
```

'This procedure is used to find a particular text in a range and return its column position

```
Function returnCol(FindText As String) As Long
```

```
    Dim s As Variant
```

'This section finds where the needed column is located at.

```
Set s = Cells.Find(What:=FindText, LookAt:=xlPart)
```

```
returnCol = s.Column
```

```
End Function
```

```
Sub WeightedAverage()
```

```

Dim returnRowArray() As Long
returnRowArray = returnRows() 'call function returnRows that is defined above
Dim i As Integer
For i = 1 To 366
    Dim rowNo As Long
    rowNo = returnRowArray(i)

    Dim rowDiff As Integer
    Dim j As Integer 'used to record which row "productivity factor" starts
    If i = 1 Then
        j = 2

    ElseIf i <> 1 Then
        j = returnRowArray(i - 1) + 1
    End If
    rowDiff = returnRowArray(i) - (j + 1)

    Dim PFdailyCol As Long
    PFdailyCol = returnCol("PFDaily")
    Cells(rowNo, PFdailyCol).Select
    Dim formula As String

    formula = "=SUMPRODUCT(R[" & -rowDiff & "]C[-2]:R[-1]C[-2],R[" & -rowDiff & "]C[-1]:R[-1]C[-1])/SUM(R[" & -rowDiff & "]C[-1]:R[-1]C[-1])"

    ActiveCell.FormulaR1C1 = Trim(formula)

Next i

End Sub

```

Appendix III VBA Code for CPM Schedule Simulation

Part 1: Main Framework

Option Explicit

Dim m_otask(200) As New cTask

Dim i As Integer

Private Sub btnStartSimulation_Click()

Dim Response As VbMsgBoxResult

Response = MsgBox("Do you want to start the simulation", vbOKCancel, "Warning")

If Response = vbOK Then

Worksheet_Activate

Else

Exit Sub

End If

End Sub

'This block of code is used to pop up a calendar when
'the cell at under SimulatedStart column is clicked

Private Sub DTPicker1_Change()

ActiveCell.value = DTPicker1.value

DTPicker1.Visible = False

End Sub

Private Sub Worksheet_SelectionChange(ByVal Target As Range)

With Me.DTPicker1

If Target.column = 9 And Target.row = 3 Or Target.column = 10 And Target.Count = 1 And
Target.row = 3 Then

.Visible = True

.Width = Target.Width + 15

.Left = Target.Left

.Top = Target.Top

.Height = Target.Height

Else

.Visible = False

```
End If
End With
```

```
'click Column Eight and Pop up dialog box for inputing relationship
```

```
If Target.column = 8 Then
```

```
    relationForm.Show
```

```
End If
```

```
End Sub
```

```
*****
```

```
Public Sub Worksheet_Activate()
```

```
    'define the column number of the lookup table
```

```
    'e.g. PF=2, means the PF values are shown on column B on the lookup table
```

```
    Const PF As Integer = 2 'This number can be changed depending on the actual spread sheet
```

```
    Const holidayNot As Integer = 5
```

```
    Const DailyWhr As Single = 6
```

```
    Dim cellRange As Range
```

```
    sheets("Test").Select 'SheetName can be changed
```

```
    Set m_otask(200) = New cTask
```

```
    'Get Excel Data and assigned to the array
```

```
    Dim taskNameCol As Long
```

```
    Dim taskIDCol As Long
```

```
    Dim workHourCol As Long
```

```
    Dim predecessorsCol As Long
```

```
    Dim simuDurationCol As Long
```

```
    Dim simuStartCol As Long
```

```
    Dim simuFinishCol As Long
```

```
    Dim simuWhrCol As Long
```

```
    Dim locationCol As Long
```

```
    Dim activityTypeCol As Long
```

```
    taskNameCol = returnCol("TaskName")
```

```
    taskIDCol = returnCol("TaskID")
```

```
    workHourCol = returnCol("WorkHour")
```

```
    locationCol = returnCol("Location")
```

```
    activityTypeCol = returnCol("ActivityType")
```

```
    predecessorsCol = returnCol("predecessors")
```

```

simuDurationCol = returnCol("SimulatedDuration")
simuStartCol = returnCol("SimulatedStart")
simuFinishCol = returnCol("SimulatedFinish")
simuWhrCol = returnCol("simulatedWorkhour")

```

```

Dim taskstartrow As Integer
taskstartrow = returnRow("taskID")

```

```

For i = 1 To ActiveSheet.UsedRange.Rows.Count - 1

```

```

    With ActiveSheet

```

```

        m_otask(i).taskName = .Cells(i + taskstartrow, taskNameCol).value
        m_otask(i).taskID = .Cells(i + taskstartrow, taskIDCol).value
        m_otask(i).location = .Cells(i + taskstartrow, locationCol).value
        m_otask(i).activityType = .Cells(i + taskstartrow, activityTypeCol).value
        m_otask(i).workHour = .Cells(i + taskstartrow, workHourCol).value
        m_otask(i).predecessors = .Cells(i + taskstartrow, predecessorsCol).value
        m_otask(i).simulatedDuration = .Cells(i + taskstartrow, simuDurationCol).value
        m_otask(i).simulatedStart = .Cells(i + taskstartrow, simuStartCol).value
        m_otask(i).simulatedFinish = .Cells(i + taskstartrow, simuFinishCol).value
        m_otask(i).simulatedWorkhour = .Cells(i + taskstartrow, simuWhrCol).value

```

```

    End With

```

```

        Dim calendarCount As Date
        Dim txtCalendarCount As String
        Dim earnedWh As Double 'Used to recrod the cumulative earned workhours
        Dim ProductivityFactor As Double
        Dim holidayYesNo As Integer
        Dim manNumber As Integer
        Dim whr As Single
        Dim whIncremental As Double 'Used to record the earned man hours in a day
        If m_otask(i).predecessors = "" Then
            calendarCount = m_otask(i).simulatedStart
            m_otask(i).rsDuration = 0

```

```

        Else

```

```

            'Look for predcessors and realtionships
            Dim predeIds() As String

```

```

predeIds = getPredeID(CStr(m_otask(i).predecessors))

*****find the latest finish time of a task's the predecessors
Dim j As Integer

'This array is used to deal with "FF" and "SF" relationship.
'And this array store potential simulated finish dates
Dim pSimulatedFinish(100) As Date

'This array is used to deal with "FS" and "SS" relationship.
'And this array store potential simulated finish dates
Dim pSimulatedStart(100) As Date

'FS: Finish-Start Relationship
'SS: Start-Start Relationship
'FF: Finish-Finish Relationship
'SF: Start-Finish Relationship

'This array is used to record the potential rsiduration duration of the
'precessors for a specific task
Dim pRsDuration(100) As Single

Dim searchChar(1 To 4) As String
    searchChar(1) = "FS"
    searchChar(2) = "SS"
    searchChar(3) = "FF"
    searchChar(4) = "SF"

'The Starting Postion of the Char to be searched
Dim searchCharPs As Integer
    searchCharPs = 0

'Define a variable to contain lags
Dim lagint(20) As Integer
'When there is only one predecessor
If UBound(predeIds) = 1 Then
    j = 1

    Dim Relationship As String
    Dim k As Integer
        k = 1
        searchCharPs = 0
    Do While searchCharPs = 0

```



```

searchCharPs = InStr(1, predeIds(1), searchChar(k))
Relationship = searchChar(k)
k = k + 1
Loop

lagint(j) = Right(predeIds(j), Len(predeIds(j)) - searchCharPs - 1)

predeIds(j) = Left(predeIds(j), searchCharPs - 1)

Select Case Relationship
    Dim l As Integer
    Dim lagSign As Integer

    Case "FS"
        If Not (lagint(j) = 0) Then
            lagSign = lagint(j) / Abs(lagint(j))
            pSimulatedStart(j) = m_otask(predeIds(j)).simulatedFinish
            'Lag should not include weekends. If weekends encountered, keep adding
            'days until weekday appears
            For l = 1 To Abs(lagint(j))
                pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
                If Weekday(pSimulatedStart(j), vbMonday) >= 5 Then
                    Do
                        pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign

                        Loop Until Weekday(pSimulatedStart(j), vbMonday) < 5
                    Else
                        pSimulatedStart(j) = pSimulatedStart(j)
                End If
            Next l
        Else
            pSimulatedStart(j) = m_otask(predeIds(j)).simulatedFinish
        End If

    Case "SS"
        If Not (lagint(j) = 0) Then
            lagSign = lagint(j) / Abs(lagint(j))
            pSimulatedStart(j) = m_otask(predeIds(j)).simulatedStart
            For l = 1 To lagint(j)
                pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
                If Weekday(pSimulatedStart(j), vbMonday) >= 5 Then
                    Do

```

```

        pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
        Loop Until Weekday(pSimulatedStart(j), vbMonday) < 5
    Else
        pSimulatedStart(j) = pSimulatedStart(j)
    End If
Next l
Else
    pSimulatedStart(j) = m_otask(predeIds(j)).simulatedStart
End If

Case "FF"
    If Not (lagint(j) = 0) Then
        lagSign = lagint(j) / Abs(lagint(j))
        pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
        For l = 1 To lagint(j)
            pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
            If Weekday(pSimulatedFinish(j), vbMonday) >= 5 Then
                Do
                    pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
                    Loop Until Weekday(pSimulatedFinish(j), vbMonday) < 5
                Else
                    pSimulatedFinish(j) = pSimulatedFinish(j)
                End If
            Next l
        Else
            pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
        End If

Case "SF"
    If Not (lagint(j) = 0) Then
        lagSign = lagint(j) / Abs(lagint(j))
        pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
        For l = 1 To lagint(j)
            pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
            If Weekday(pSimulatedFinish(j), vbMonday) >= 5 Then
                Do
                    pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign

                    Loop Until Weekday(pSimulatedFinish(j), vbMonday) < 5
                Else
                    pSimulatedFinish(j) = pSimulatedFinish(j)
                End If
            Next l

```

```

Else
    pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
End If
End Select
If lagint(j) <> 0 Then
    m_otask(i).rsDuration = 0
Else
    m_otask(i).rsDuration = m_otask(predeIds(j)).rsDuration
End If

```

Else 'When there are several predecessors

```

For j = 1 To UBound(predeIds)

```

```

    k = 1
    searchCharPs = 0
Do While searchCharPs = 0
    searchCharPs = InStr(1, predeIds(j), searchChar(k))
    Relationship = searchChar(k)
    k = k + 1
Loop

```

```

lagint(j) = Right(predeIds(j), Len(predeIds(j)) - searchCharPs - 1)

```

```

predeIds(j) = Left(predeIds(j), searchCharPs - 1)

```

```

Select Case Relationship

```

```

    Case "FS"

```

```

        If Not (lagint(j) = 0) Then

```

```

            lagSign = lagint(j) / Abs(lagint(j))
            pSimulatedStart(j) = m_otask(predeIds(j)).simulatedFinish
            'Lag should not include weekends. If weekends encountered, keep adding
            'days until weekday appears
            For l = 1 To Abs(lagint(j))
                pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
                If Weekday(pSimulatedStart(j), vbMonday) >= 5 Then
                    Do
                        pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign

```

```

        Loop Until Weekday(pSimulatedStart(j), vbMonday) < 5
    Else
        pSimulatedStart(j) = pSimulatedStart(j)
    End If
Next l
Else
    pSimulatedStart(j) = m_otask(predeIds(j)).simulatedFinish

End If

Case "SS"
    If Not (lagint(j) = 0) Then
        lagSign = lagint(j) / Abs(lagint(j))
        pSimulatedStart(j) = m_otask(predeIds(j)).simulatedStart
        For l = 1 To lagint(j)
            pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
            If Weekday(pSimulatedStart(j), vbMonday) >= 5 Then
                Do
                    pSimulatedStart(j) = pSimulatedStart(j) + 1 * lagSign
                    Loop Until Weekday(pSimulatedStart(j), vbMonday) < 5
                Else
                    pSimulatedStart(j) = pSimulatedStart(j)
                End If
            Next l
        Else
            pSimulatedStart(j) = m_otask(predeIds(j)).simulatedStart
        End If
    End If

Case "FF"
    If Not (lagint(j) = 0) Then
        lagSign = lagint(j) / Abs(lagint(j))
        pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
        For l = 1 To lagint(j)
            pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
            If Weekday(pSimulatedFinish(j), vbMonday) >= 5 Then
                Do
                    pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
                    Loop Until Weekday(pSimulatedFinish(j), vbMonday) < 5
                Else
                    pSimulatedFinish(j) = pSimulatedFinish(j)
                End If
            End If
        End If
    End If

```

```

        Next l
    Else
        pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
    End If

    Case "SF"
        If Not (lagint(j) = 0) Then
            lagSign = lagint(j) / Abs(lagint(j))
            pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
            For l = 1 To lagint(j)
                pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign
                If Weekday(pSimulatedFinish(j), vbMonday) >= 5 Then
                    Do
                        pSimulatedFinish(j) = pSimulatedFinish(j) + 1 * lagSign

                        Loop Until Weekday(pSimulatedFinish(j), vbMonday) < 5
                    Else
                        pSimulatedFinish(j) = pSimulatedFinish(j)
                    End If
                End If
            Next l
        Else
            pSimulatedFinish(j) = m_otask(predeIds(j)).simulatedFinish
        End If
    End Select

Next j

End If

m_otask(i).simulatedStart = Max(pSimulatedStart())
Dim IndexofMax As Integer
IndexofMax = IndexMaxofArray(pSimulatedStart())
If lagint(IndexofMax) = 0 Then
    m_otask(i).rsDuration = m_otask(predeIds(IndexofMax)).rsDuration

Else
    m_otask(i).rsDuration = 0

End If

calendarCount = m_otask(i).simulatedStart
ActiveSheet.Cells(i + taskstartrow, simuStartCol).value = calendarCount
End If

```

```
txtCalendarCount = WorksheetFunction.Text(calendarCount, "mm/dd/yyyy")
```

```
'rsDuration is used to record the residual of the day that can be used
```

```
'to continue the next task
```

```
Dim rsDuration As Single
```

```
'Cumulative Duration is used to store the cumulative duration
```

```
Dim cumulativeDuration As Single
```

```
Dim lookupLocation As String
```

```
lookupLocation = m_otask(i).location
```

```
Dim lookupActivity As String
```

```
lookupActivity = m_otask(i).activityType
```

```
*****
```

```
'For the project's starting date, there is no residuration duration
```

```
If i = 1 Then
```

```
    m_otask(i).rsDuration = 0
```

```
    earnedWh = 0
```

```
Else
```

```
    cumulativeDuration = m_otask(i).rsDuration
```

```
    ProductivityFactor = rtrValue(txtCalendarCount, PF)
```

```
    holidayYesNo = rtrValue(txtCalendarCount, holidayNot)
```

```
    'Return the number of the ManPower using Function rtManNo
```

```
    manNumber = rtManNo(lookupLocation, lookupActivity)
```

```
    whr = rtrValue(txtCalendarCount, DailyWhr)
```

```
*****
```

```
'A task starts in the middle of a day
```

```
If m_otask(i).rsDuration > 0 Then
```

```
    earnedWh = ErndWh(ProductivityFactor, holidayYesNo, manNumber, whr _  
                    * m_otask(i).rsDuration)
```

```
'A task starts from a new day
```

```
Else
```

```
    earnedWh = ErndWh(ProductivityFactor, holidayYesNo, manNumber, whr)
```

```
    cumulativeDuration = 1
```

```
End If
```

```
*****
```

```
End If
```

```
Do
  If i = 1 Then
    txtCalendarCount = WorksheetFunction.Text(calendarCount, "mm/dd/yyyy")

  Else
    txtCalendarCount = WorksheetFunction.Text(DateAdd("d", 1, calendarCount),
"mm/dd/yyyy")

  End If
  ProductivityFactor = rtrValue(txtCalendarCount, PF)
  holidayYesNo = rtrValue(txtCalendarCount, holidayNot)

  'Return the number of the ManPower using Function rtManNo
  manNumber = rtManNo(lookupLocation, lookupActivity)

  whr = rtrValue(txtCalendarCount, DailyWhr)

  whIncremental = ErndWh(ProductivityFactor, holidayYesNo, manNumber, whr)

  earnedWh = earnedWh + whIncremental

  cumulativeDuration = cumulativeDuration + holidayYesNo

  'This if statement is based on the statement that the first task would be
  'different than other tasks.
  If i = 1 Then
    Cells(i + taskstartrow, simuFinishCol).value = calendarCount
  Else
    Cells(i + taskstartrow, simuFinishCol).value = Max(DateAdd("d", 1, calendarCount),
pSimulatedFinish())
  End If

  calendarCount = DateAdd("d", 1, calendarCount)
Loop Until earnedWh >= m_otask(i).workHour
'residualwh is used to record the residual of the cumulative earned hours
'that are greater than the quantity of work hours for a specific task
m_otask(i).residualWh = earnedWh - m_otask(i).workHour
m_otask(i).rsDuration = m_otask(i).residualWh / whIncremental
```

```

m_otask(i).simulatedFinish = Cells(i + taskstartrow, simuFinishCol).value
Cells(i + taskstartrow, simuDurationCol).value = cumulativeDuration - m_otask(i).rsDuration

```

'Assign the value of the cell to the object member

```

m_otask(i).simulatedDuration = Cells(i + taskstartrow, simuDurationCol).value

```

'Cucluate the workhours spends on a task under current simulation

```

m_otask(i).simulatedWorkhour = m_otask(i).simulatedDuration * manNumber * whr
Cells(i + taskstartrow, simuWhrCol).value = m_otask(i).simulatedWorkhour

```

On Error GoTo Errhandler

Next i

Errhandler: Exit Sub

End Sub

'This fuction is used to lookup productivity factor, Holiday or not,

'number of workforce, and hours per day corresponding to the date

'The productivity lookup tables' names will be the year of the dates

*****This part of code has been validated

Private Function rtrValue(lkupDateValue As String, lookupCol As Integer) As Double

Dim YearofDates As String

YearofDates = CStr(Year(lkupDateValue))

Dim cellRange As Range

Set cellRange = worksheets(YearofDates).Range("A2:G370")

rtrValue = WorksheetFunction.VLookup(lkupDateValue, cellRange, lookupCol)

End Function

'This function is used to number of Manpower used on each each

'correponding task's location and activityType at the ManPower Worksheet

Private Function rtManNo(lkupLocation As String, lkupActivityType As String) As Integer

Dim i As Integer

'Location is used to subsititute the column number of "Location"

Const location As Integer = 1

'ActivityType is used to substitute the column number of "ActivityType"

Const activityType As Integer = 2

'ManPower is used to substitute the column number of "ManPower"

Const ManPower As Integer = 3


```

Dim a As String
Dim b As String
i = 1
Do
    i = i + 1
    a = worksheets("ManPower").Cells(i, location)
    b = worksheets("ManPower").Cells(i, activityType)

Loop Until (a = lkupLocation) And (b = lkupActivityType)

rtManNo = worksheets("ManPower").Cells(i, ManPower)

On Error GoTo Errhandler

Errhandler: Exit Function

End Function

'This function is used to calculate the earned workhours
Private Function ErndWh(PF As Double, holiday As Integer, man As Integer, whr As Single) As Double
    ErndWh = PF * holiday * man * whr
End Function

'This procedure is used to find a particular text in a range and return its column position
Public Function returnCol(findText As String) As Long
    Dim s As Variant
    'This section finds where the needed column is located at.
    Set s = Cells.Find(What:=findText, LookAt:=xlWhole)
    returnCol = s.column
End Function

Public Function returnRow(findText As String) As Long
    Dim s As Variant
    Set s = Cells.Find(What:=findText, LookAt:=xlWhole)
    returnRow = s.row
End Function

'Method used to Get a tasks' predecessorr's ID's

Public Function getPredeID(str As String) As String()
    Dim id() As String
    Dim position() As Integer
    'Caluculate the occurence of "," in a string

```

```

Dim j As Integer
j = Len(str) - Len(Replace(str, ",", ""))

ReDim position(j) As Integer
ReDim id(j + 1) As String
If j = 0 Then
    id(j + 1) = str
    getPredeID = id
Else
    Dim i As Integer
    For i = 1 To j
        If i = 1 Then
            position(i) = InStr(i, str, ",", vbTextCompare)
            id(i) = Left(str, position(i) - 1)
        Else
            position(i) = InStr(position(i - 1) + 1, str, ",", vbTextCompare)
            id(i) = Mid(str, position(i - 1) + 1, position(i) - position(i - 1) - 1)
        End If
    Next i
    id(j + 1) = Right(str, Len(str) - position(j))
    getPredeID = id
End If
End Function

```

```

Private Sub CommandButton2_Click()
    Range("A65536").End(xlUp).Select
    ActiveSheet.Cells(33, "D").value = Range("A65536").End(xlUp)
End Sub

```

***Reference <http://www.visualbasic.happycodings.com/Applications-VBA/code8.html>

```

Function Max(ParamArray avValues() As Variant) As Variant
    Dim vThisItem As Variant, vThisElement As Variant

    On Error Resume Next
    For Each vThisItem In avValues
        If IsArray(vThisItem) Then
            For Each vThisElement In vThisItem
                Max = Max(vThisElement, Max)
            Next
        Else
            If vThisItem > Max Then
                If Not IsEmpty(vThisItem) Then

```

```

        Max = vThisItem
    End If
    ElseIf IsEmpty(Max) Then
        Max = vThisItem
    End If
End If
Next
On Error GoTo 0
End Function

```

```

Function Min(ParamArray avValues() As Variant) As Variant
    Dim vThisItem As Variant, vThisElement As Variant

```

```

    On Error Resume Next
    For Each vThisItem In avValues
        If IsArray(vThisItem) Then
            For Each vThisElement In vThisItem
                Min = Min(vThisElement, Min)
            Next
        Else
            If vThisItem < Min Then
                If Not IsEmpty(vThisItem) Then
                    Min = vThisItem
                End If
            ElseIf IsEmpty(Min) Then
                Min = vThisItem
            End If
        End If
    Next
    On Error GoTo 0
End Function

```

***Reference <http://www.freevbcode.com/ShowCode.asp?ID=8459>

```

Function IndexMaxofArray(theArray As Variant) As Integer

```

```

    Dim i As Integer
    Dim MaxIntegersIndex As Integer
    MaxIntegersIndex = 0

```

```

    For i = 1 To UBound(theArray)
        If theArray(i) > theArray(MaxIntegersIndex) Then
            MaxIntegersIndex = i
        End If
    Next

```

```
IndexMaxofArray = MaxIntegersIndex  
End Function
```

'Class Definition:

```
Option Explicit
```

```
Private m_taskID As Long  
Private m_taskName As String  
Private m_location As String  
Private m_activityType As String  
Private m_workHour As Integer  
Private m_plannedStart As Date  
Private m_plannedFinish As Date  
Private m_predecessors As String  
Private m_simulatedStart As Date  
Private m_simulatedFinish As Date  
Private m_simulatedDuration As Single  
'm_simulatedWorkhour is sued to record the workhours needed to  
'accomplish a specific task  
Private m_simulatedWorkhour As Single  
  
'residualWh is used to record the residual of workhours that could be  
'used to do other work when one task is finished before the end of that  
'day  
Private m_residualWh As Single  
  
'rsDuration is used to record the residual of a day that could be used to  
' do other work when one task if finished before the end of that day  
Private m_rsDuration As Single  
  
Private m_xlWksht As Worksheet  
  
Property Get taskID() As Long  
    taskID = m_taskID  
End Property  
Property Let taskID(newTaskID As Long)  
    m_taskID = newTaskID  
End Property  
  
Property Get taskName() As String  
    taskName = m_taskName  
End Property
```

```

Property Let taskName(newTaskName As String)
    m_taskName = newTaskName
End Property

Property Get location() As String
    location = m_location
End Property
Property Let location(newLocation As String)
    m_location = newLocation
End Property

Property Get activityType() As String
    activityType = m_activityType
End Property
Property Let activityType(newActivityType As String)
    m_activityType = newActivityType
End Property

Property Get workHour() As Integer
    workHour = m_workHour
End Property

Property Let workHour(newWorkhour As Integer)
    m_workHour = newWorkhour
End Property
Property Get plannedstart() As Date
    plannedstart = m_plannedStart
End Property

Property Let plannedstart(newPlannedStart As Date)
    m_plannedStart = newPlannedStart
End Property
Property Get predecessors() As String
    predecessors = m_predecessors
End Property
Property Let predecessors(newpredecessors As String)
    m_predecessors = newpredecessors
End Property

Property Get simulatedStart() As Date
    simulatedStart = m_simulatedStart
End Property

Property Let simulatedStart(newSimulatedStart As Date)

```

```
    m_simulatedStart = newSimulatedStart  
End Property
```

```
Property Get simulatedFinish() As Date  
    simulatedFinish = m_simulatedFinish  
End Property
```

```
Property Let simulatedFinish(newSimulatedFinish As Date)  
    m_simulatedFinish = newSimulatedFinish  
End Property
```

```
Property Get simulatedDuration() As Single  
    simulatedDuration = m_simulatedDuration  
End Property
```

```
Property Let simulatedDuration(newSimulatedDuration As Single)  
    m_simulatedDuration = newSimulatedDuration  
End Property
```

```
Property Get simulatedWorkhour() As Single  
    simulatedWorkhour = m_simulatedWorkhour  
End Property
```

```
Property Let simulatedWorkhour(newSimulatedWorkhour As Single)  
    m_simulatedWorkhour = newSimulatedWorkhour  
End Property
```

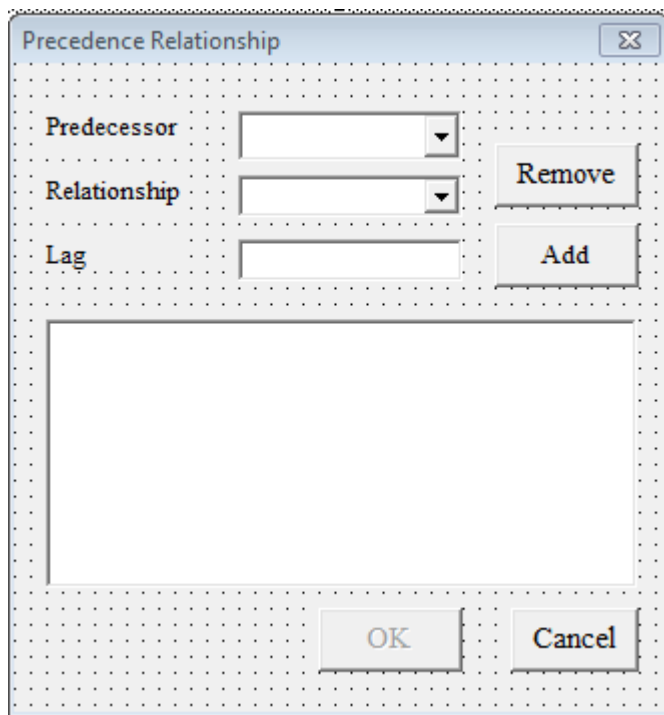
```
Property Get residualWh() As Single  
    residualWh = m_residualWh  
End Property
```

```
Property Let residualWh(newResidualWh As Single)  
    m_residualWh = newResidualWh  
End Property
```

```
Property Get rsDuration() As Single  
    rsDuration = m_rsDuration  
End Property
```

```
Property Let rsDuration(newRsDuration As Single)  
    m_rsDuration = newRsDuration  
End Property
```

Part 2: Precedence Relationship Popup Form



The image shows a Windows-style dialog box titled "Precedence Relationship". It has a close button (X) in the top right corner. The dialog is set against a dotted grid background. It contains three input fields: "Predecessor" (a dropdown menu), "Relationship" (a dropdown menu), and "Lag" (a text box). To the right of the "Predecessor" and "Relationship" fields is a "Remove" button. To the right of the "Lag" field is an "Add" button. Below these fields is a large empty rectangular box. At the bottom of the dialog are "OK" and "Cancel" buttons.

VBA Code:

```
Private Sub btnAdd_Click()  
    Dim txtRelation As String  
    Dim lag As String  
  
    If txtLag.value >= 0 Then  
        lag = "+" & txtLag.value  
    Else  
        lag = txtLag.value  
    End If  
  
    Select Case cmbRelation.value  
        Case "Finish-to-Start"  
            txtRelation = "FS"  
        Case "Start-to-Start"  
            txtRelation = "SS"  
        Case "Start-to-Start"  
            txtRelation = "SS"  
        Case "Start-to-Start"  
            txtRelation = "SS"  
    End Select  
    lstPredecessor.AddItem ((cmbPredecessor.value & txtRelation _
```

```

        & lag))

    If lstPredecessor.ListCount = 0 Then
        btnOK.Enabled = False
    Else
        btnOK.Enabled = True
    End If

End Sub

Private Sub btnCancel_Click()
    End
End Sub

Private Sub btnOK_Click()
    Dim concatStr As String
    Dim appendStr As String
    For i = lstPredecessor.ListCount - 1 To 0 Step -1
        appendStr = lstPredecessor.List(i)
        concatStr = Trim(appendStr + ", " + concatStr)
    Next

    worksheets("Test").Activate
    ActiveCell.value = Left(concatStr, Len(concatStr) - 1)

    End
End Sub

'Remove slected items in listbox
Private Sub btnRemove_Click()

    For i = lstPredecessor.ListCount - 1 To 0 Step -1
        If lstPredecessor.Selected(i) Then
            lstPredecessor.RemoveItem i
        End If

        If lstPredecessor.ListCount = 0 Then
            btnOK.Enabled = False
        Else
            btnOK.Enabled = True
        End If

    Next
End Sub

```



```

Private Sub lstPredecessor_Click()
    If lstPredecessor.ListCount = 0 Then
        btnOK.Enabled = False
    Else
        btnOK.Enabled = True
    End If
End Sub

Private Sub UserForm_Activate()

    With cmbRelation
        .AddItem ("Finish-to-Start")
        .AddItem ("Start-to-Start")
        .AddItem ("Start-to-Finish")
        .AddItem ("Finish-to-toFinish")
    End With

    Dim taskstartrow As Integer
    taskstartrow = worksheets("Test").returnRow("TaskID")

    worksheets("Test").Activate
    With cmbPredecessor
        For i = 1 To worksheets("Test").UsedRange.Rows.Count - 1

            .AddItem (Cells((i + taskstartrow), "A"))

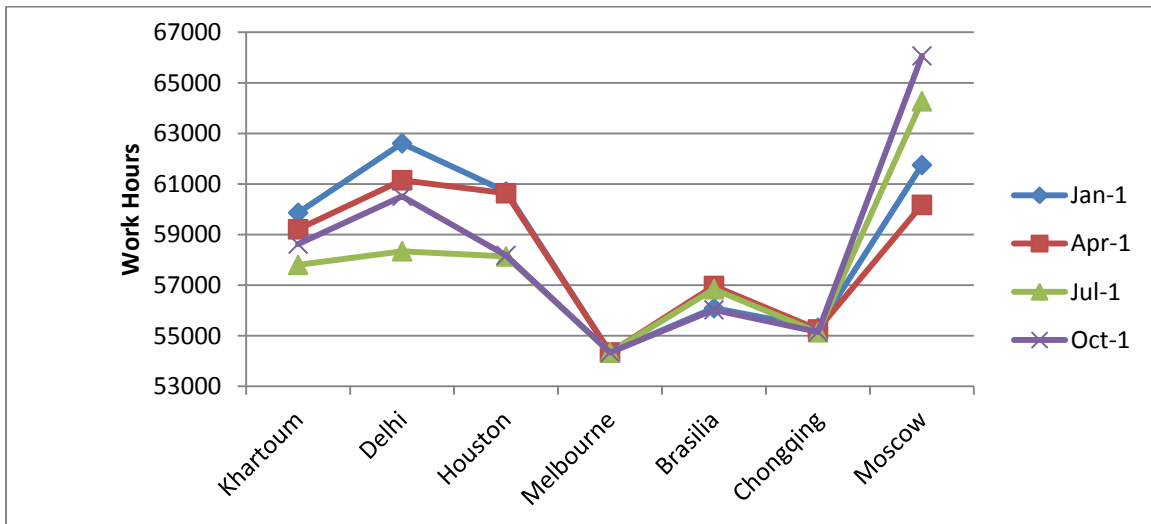
        Next i
    End With
End Sub

```

Appendix IV Project Start Date - Location 2 Way ANOVA

i. Project Start Date - Location 2 Way ANOVA (HADCM3-SresA1b)

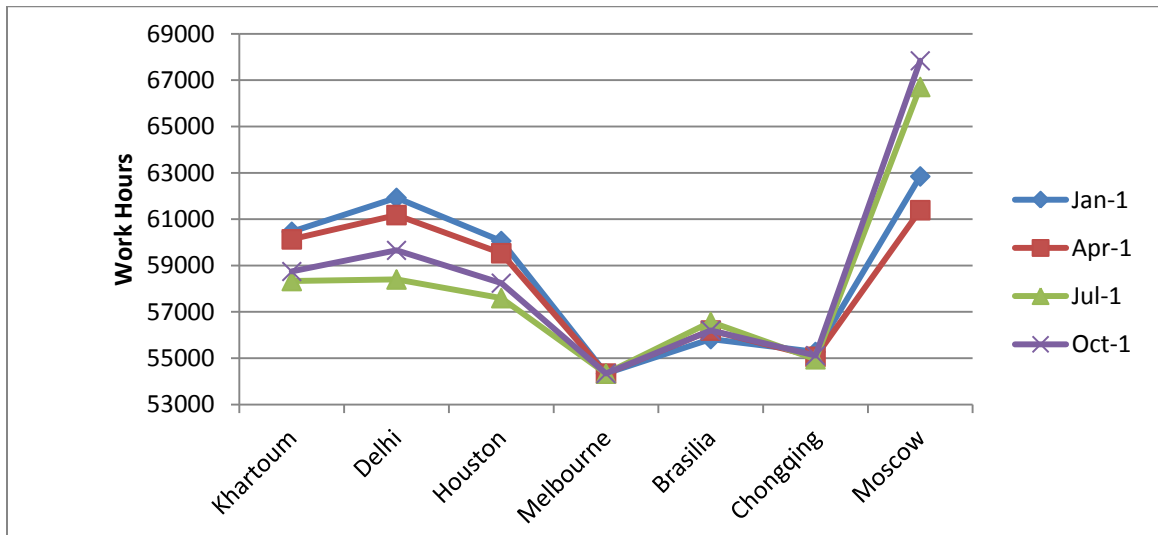
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.32E+10	27	4.90E+08	43.625	.000
Intercept	4.62E+12	1	4.62E+12	4.12E+05	0.000
StartDate	1.24E+08	3	4.12E+07	3.670	.012
City	1.13E+10	6	1.89E+09	168.353	.000
StartDate * City	1.78E+09	18	9.91E+07	8.826	.000
Error	1.50E+10	1333	1.12E+07		
Total	4.65E+12	1361			
Corrected Total	2.82E+10	1360			



The Plot of Project Start Date - Location Interaction (HADCM3-SresA1b)

ii. Project Start Date - Location 2 Way ANOVA (HADCM3-SresA2)

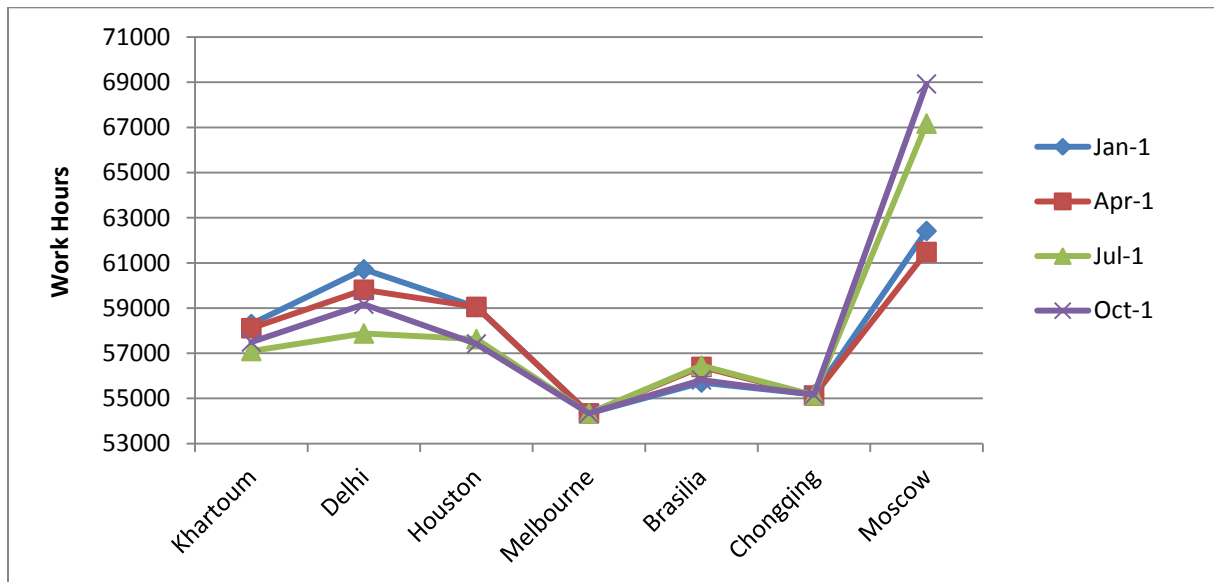
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.65E+10	27	6.12E+08	46.618	.000
Intercept	4.51E+12	1	4.51E+12	3.44E+05	0.000
StartDate	6.75E+07	3	2.25E+07	1.715	.162
City	1.45E+10	6	2.42E+09	184.087	.000
StartDate * City	1.97E+09	18	1.09E+08	8.331	.000
Error	1.70E+10	1395	1.31E+07		
Total	4.55E+12	1323			
Corrected Total	3.35E+10	1322			



The Plot of Project Start Date - Location Interaction (HADCM3-SresA2)

iii. Project Start Date - Location 2 Way ANOVA (HADCM3-SresB1)

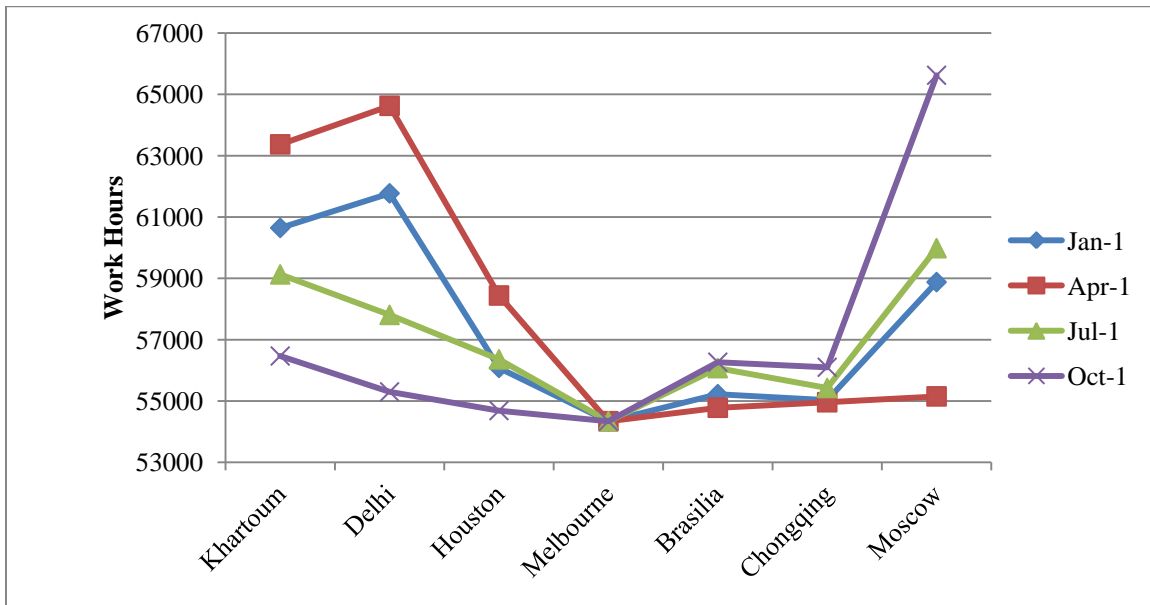
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.70E+10	27	6.30E+08	51.347	.000
Intercept	4.58E+12	1	4.58E+12	3.73E+05	0.000
StartDate	5.79E+07	3	1.93E+07	1.572	.194
City	1.48E+10	6	2.47E+09	201.085	.000
StartDate * City	2.23E+09	18	1.24E+08	10.089	.000
Error	1.64E+10	1335	1.23E+07		
Total	4.62E+12	1363			
Corrected Total	3.34E+10	1362			



The Plot of Project Start Date - Location Interaction(HADCM3-SresB1)

iv. Project Start Date - Location 2 Way ANOVA (NOAA-SresA1b)

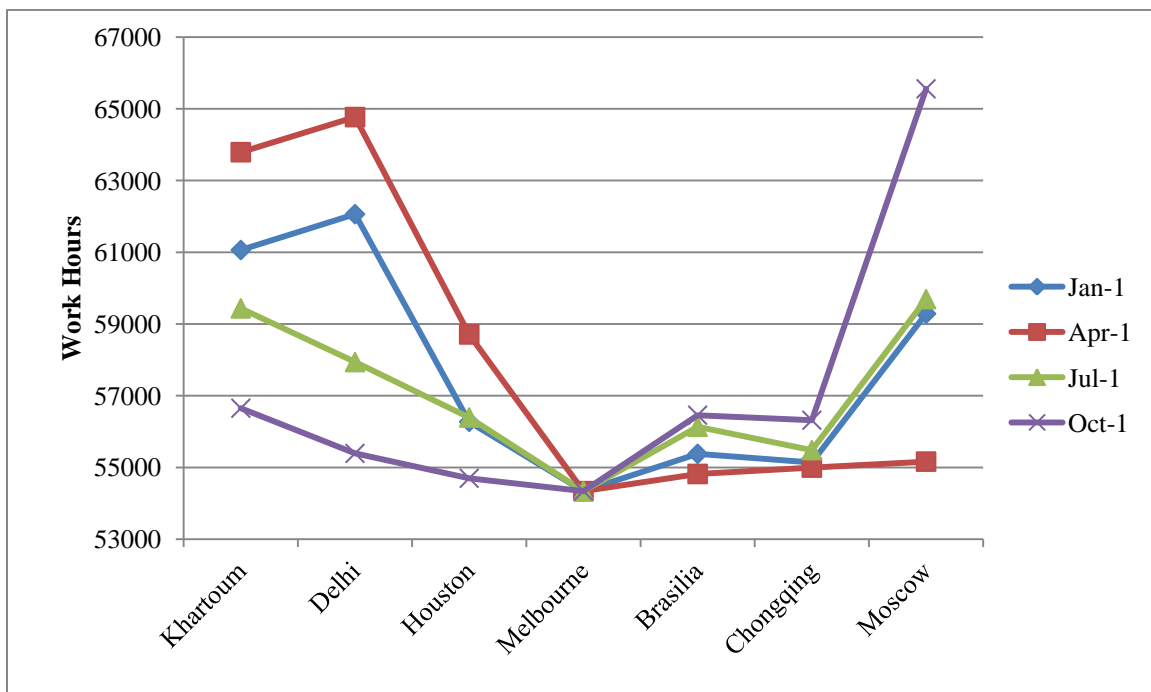
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.40E+10	27	5.19E+08	436.608	0.000
Intercept	4.48E+12	1	4.48E+12	3.77E+06	0.000
StartDate	2.13E+08	3	7.10E+07	59.732	.000
City	7.09E+09	6	1.18E+09	994.085	0.000
StartDate * City	6.68E+09	18	3.71E+08	312.303	0.000
Error	1.59E+09	1335	1.19E+06		
Total	4.50E+12	1363			
Corrected Total	1.56E+10	1362			



The Plot of Project Start Date - Location Interaction(NOAA-SresA1b)

v. Project Start Date - Location 2 Way ANOVA (NOAA-SresA2)

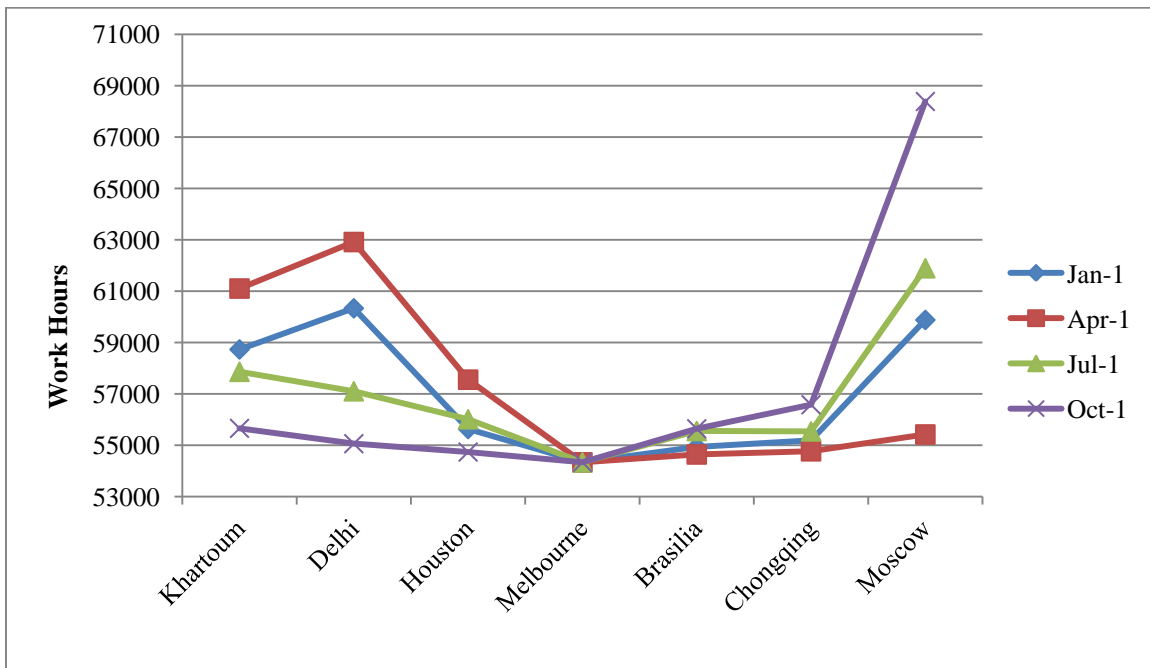
Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.45E+10	27	5.36E+08	3.92E+02	0.000
Intercept	4.50E+12	1	4.50E+12	3.29E+06	0.000
StartDate	2.54E+08	3	8.47E+07	6.19E+01	.000
City	7.41E+09	6	1.23E+09	9.03E+02	0.000
StartDate * City	6.78E+09	18	3.77E+08	2.75E+02	0.000
Error	1.83E+09	1335	1.37E+06		
Total	4.52E+12	1363			
Corrected Total	1.63E+10	1362			



The Plot of Project Start Date - Location Interaction(NOAA-SresA2)

vi. Project Start Date - Location 2 Way ANOVA (NOAA-SresB1)

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.44E+10	27	5.33E+08	419.147	0.000
Intercept	4.44E+12	1	4.44E+12	3.49E+06	0.000
StartDate	2.74E+07	3	9.13E+06	7.175	.000
City	7.40E+09	6	1.23E+09	969.329	0.000
StartDate * City	7.01E+09	18	3.89E+08	305.900	0.000
Error	1.70E+09	1334	1.27E+06		
Total	4.45E+12	1362			
Corrected Total	1.61E+10	1361			



The Plot of Project Start Date - Location Interaction(NOAA-SresB1)