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Visualizing the Constructability of a Steel Structure Using Building Information Modeling and Game Simulation

Mohammed Al Dafaay
Western Michigan University

VISUALIZING THE CONSTRUCTABILITY OF A STEEL STRUCTURE USING BUILDING INFORMATION MODELING AND GAME SIMULATION

by

Mohammed Al Dafaay

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Thesis Committee:

Yufeng Hu, Ph.D., Chair
Jiansong Zhang, Ph.D.
Jun-Seok Oh, Ph.D.

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Mohammed Al Dafaay, M.S.E

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This research aims to visualize a steel structural design to: (1) analyze its constructability, and (2) support collaboration between project participants at the planning stage. The visualization uses Building Information Modeling (BIM) and game engine simulation to develop a realistic interactive simulation for constructability analysis. A case study experiment was conducted on visualizing the erection process of a steel structure to facilitate the understanding of needed construction operation. The simulation incorporated construction domain knowledge through various entity components and predefined interaction rules. Results showed that through such a visualization method, field operation can be observed in real-time at the planning stage to achieve constructability analysis objectives that is going to help with: (1) knowledge and information sharing among project participants, (2) decision making in a timely manner, and (3) workers' education and training in field operation environment.

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Mohammed Al Dafaay

DEDCATION

To my father who taught me how to face obstacles with persistence and strength,

To the kindest woman in the world, my mother,

To my caring and supportive brothers and sisters

I dedicate this work for you all with respect and love!

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CHAPTER 1

Introduction

According to the Construction Industry Institute (CII 1986), Constructability is “the optimum use of construction knowledge and experience in planning, design, procurement and field operation to achieve overall objectives.” It is widely accepted that constructability considerations should be incorporated into early phases of a construction project, such as feasibility study, conceptual planning, design, procurement, in addition to the field construction phase where constructability needs to be implemented to the fullest degree possible (UT at Austin, 1997). For this purpose, a large amount of information need to be communicated between project team members effectively in a timely manner to achieve the potential constructability benefits. The traditional approach to communicate this information, such as using paper-based documents, 2D drawings and verbal communications, lacks effectiveness and can cause schedule delay (Ganah et al. 2005). Most of the traditional constructability analysis tasks were conducted manually. Such a manual approach can be error prone as it depends on the experts’ knowledge and experience. His/her perspective will dictate the analysis results without exchanging knowledge and information with other project stakeholders. According to (Cheng and Teizer, 2013), a significant deficiency in the traditional information delivery process was that the project team was not always in the position to make rapid and correct decisions due to information unavailability or insufficiency. Considering the significant difference between architects’ and engineers’ perspectives towards any construction operation, a collaboration based on effective communication is strongly needed to share views and understating between different parties related to this operation. Three-Dimensional (3D) visualization can facilitate such communication for a shared understanding across interdisciplinary groups (Bouchlaghem et al. 2005). To better understand the constructability process, there is a need to integrate the following two main aspects into consideration so that the overall performance of a construction project can be improved: (1) construction knowledge, and (2) construction experience. The optimized use of construction knowledge and experience in the design phase can enable an effective construction process to achieve overall project objectives (Jiang and Robert 2014). The separation between design and construction phases, especially in a traditional delivery method (e.g., design bid-build), impedes the collaboration between designers and construction personnel, leading to the lack of constructability consideration in the planning and design phases. Methods are needed to convey construction knowledge and experience to the design professionals, to bridge this gap usually happening between design and construction phases. Even though constructability may not necessarily be the most important consideration in a construction project, yet the inclusion of construction domain knowledge and experience into the planning and design phases would enable parties to reduce installation cost and/or improve safety conditions during construction (Jergeas and Put 2001). Additionally, the two most crucial factors affecting project time, cost, and quality performance - namely, labor and materials - can also be categorized as factors affecting constructability. They also need to be well planned in early phases of a project, which can be coordinated with constructability analysis (Jergeas and Put 2001).

Because of such expected benefits of constructability analysis, many construction companies began to conduct constructability review in their conceptual planning, design, procurement, and field operation phases of a project as a fundamental check of constructability (CII 1986). Nonetheless, the constructability analysis usually comes to the scene as a sophisticated task; as the communication and collaboration challenges need to be mitigated in order to achieve project objectives. In other words, constructability analysis involves organizing different disciplines effectively to improve the buildability and reduce risk levels of the project by checking the compliance with construction codes, documents and standards as early as possible (Ogburn and El-adaway, 2014). Consequently, design individuals obtain construction knowledge through being involved in the construction process so that they can improve the constructability of their designs. The improvement was by virtue of their insights gained through communication and collaboration with engineers, construction and field operation experts, which in turn can be used toward achieving the ultimate goal of constructability (Pulaski and Horman, 2005, Arditi et al. 2002). Moreover, according to (Pulaski and Horman, 2005), the knowledge on constructability resides in the brains of construction experts and is difficult to be verbally shared. It must be stimulated out of the box and shared between participants in the right time at the most effective stage of design process to be made full use of. In fact, due to the uniqueness of each project in terms of time, cost, quality, and safety; the issues on productivity appear in various ways for different projects. However, this knowledge must be made interchangeably transferable between experts and construction crews. Otherwise it will be difficult to transfer such knowledge to the operational personnel in the crews, who need to use the knowledge to make sure that their skill sets suffice to perform the tasks.

In addition, construction project complexity rapidly increases due to: (1) higher standards in achieving construction management goals; (2) constantly changing technologies; and (3) globalized economic and environmental issues (Gidado,1996, Kim and Wilemon, 2003). With the increasing complexity in many aspects such as functional requirements and aesthetic requirements, the need for a more advanced approach to conduct the constructability analysis becomes evident. One good way to satisfy such need is through leveraging advanced technologies such as BIM visualization and game simulation.

Research Problem and Motivation

In the last few decades, building designs have become more complex due to the relentless pace of technology advancement. Whereas demands of efficiency for construction operations stays a primary objective in any construction project. Consequently, constructability analysis is crucial to measure the connectivity between construction knowledge and experience and the construction execution to achieve project objectives. According to Jiang et al. (2013), constructability has its own tools for the analysis process which can be divided into two categories: knowledge-based systems and quantitative analysis systems. In addition, rule-based checking through the employment of Building Information Modeling (BIM) has been explored to achieve the automated constructability review process (Jiang and Robert 2014).

This research aims to develop a visual-based constructability analysis method leveraging BIM and game simulation combinedly to create an interactive virtual simulation. Visualization serves as an effective communication method at both the schedule level and the operation level (Kamat 2011). Also, visualizing construction operations dynamically depicts the interactions of the various resources (e.g., materials, labors, and equipment) that are involved in building the facility (Kamatand and Martinez 2001).

Existing visualization tools have shown their limitations to generate interactive virtual simulation or create dynamic real-time visualization, and/or failure to simulate the physical properties of the components during the visualization process. Game engine-based visualization tools open the horizon towards more interactivity and virtual-world observation to account for construction knowledge and experiences. The entity component system in game engines such as Unity 3D and Unreal engine is not only capable of dynamically visualizing an interactive environment, but is also characterized with data compatibility and interoperability among other

3D computer aided design software (CAD), including but are not limited to Blender, 3ds Max, Rivet. This makes the game engines well suited tool for developing a method to visualize the constructability of a building design for review and analysis.

Research Scope and Definition

This research studies the visual representations of steel structure erection and construction processes that helps the architects, engineers and construction team to make better decisions in their designs and generate digital-checked model ready for prefabrication. Additionally, this research is to enhance the knowledge in terms of whether/how the use of visualization and simulation tools can improve the constructability of steel structure design by developing an interactive communication environment that is intended to assist the collaboration between designers and construction team to achieve overall projects objectives.

Research Objective and Contribution

This research investigated the value of visualizing and simulating constructability of a steel structure installation, in an interactive and realistic virtual world scene. Unity3D game engine was used to create the simulation and visualization, where the information of the facility came from a BIM model. The case study experiment showed that the simulation and visualization helped identify productivity and safety issues and helped analyzing alternative construction methods to solve such issues. Such a visualization and simulation can be used at the planning and design stages of a project to help: (1) share knowledge between stakeholders; (2) support decision makings; and (3) raise workers’ awareness of their operational environment.

Thesis Structure

Chapter 1: Introduction

This chapter Gives a general background and outlines about this research and discusses the problem addressed by the research. This chapter also demonstrate the scope, definition, objectives and contribution of the research as well as clarifying how the thesis structured.

Chapter 2: Literature Review

This chapter reviews the literature in the fields of constructability and its analysis, BIM and unity3D game engine, illustrating the capability of conducting such a technology going to improve constructability analysis.

Chapter 3: Methodology

This chapter demonstrate the research process and methods conducted to develop visualized/simulated three-dimensional model to analyze constructability and contributions to explicitly unveil the constructability concepts and support design decision making proactively.

Chapter 4: Experiment

This chapter illustrates the experiment utilized to evaluate and analyze constructability, different analysis scenarios and implementation were also discussed in this chapter.

Chapter 5: Conclusion

This chapter describes the outcome of conducting constructability analysis in the experiment phase and its interpretation.

CHAPTER 2

Literature Review

In order to expand upon the fundamental of the constructability analysis, this chapter presents the review of previous literatures dealt with constructability visualization and simulation concepts using Building Information Modeling (BIM) and Unity3D game engine. The goal of the review is to recognize the previous efforts that has been conducted to achieve these concepts and determine the gaps to be address throughout this research.

Constructability Concept and Definition

In 1980s, the constructability concept was first introduced to the construction industry. Since then, a tremendous study emerges to conduct a research about how to efficiently implement the constructability concept in real world practices. A multiple constructability concepts has been formed depending on project objectives and constrain. In that sense and in order to make sure that the construction feasibility is considered in each and every phase of the project (CII, 1986), Construction Industry Institute (CII) define the constructability as "the optimum use of construction knowledge and experience in planning, design, procurement and field operation to achieve overall objectives.". In same manner, a Buildability term uses in United Kingdom and its defines as "the extent to which the design of the building facilitates ease of construction, subject to overall requirements for the completed building." ("Buildability", 1983). Based on those definitions, (Fischer and Tatum, 1997) alters them and come up with a definition targeting the design-construction interface in particular: "the constructability is the extent to which the design of the building facilitated ease of construction, subject to the requirements of construction methods.". regardless of the difference in the terminology between constructability and buildability, both concepts are leveraging the construction knowledge and experience to achieve project objectives.

To understand the concept of constructability entirely, (Hanlon and Sanvido, 1995) grouped it into five categories and identified the attributes associated with each category as shown in figure 2.1

1. Design rules: its accommodate design rules attributes such as design applicability, dimensions and details that has impacts on the design concept based on the work of (Fischer, 1991). (Fischer and Tatum, 1997) identify those attributes to (1) application knowledge (2) layout knowledge (3) dimensioning knowledge (4) detailing knowledge and (5) Exogenous knowledge.
2. Resource constraints: its describe the resource requirements or impacts on the concept implementation. Based on the resource type, its divided into nine subcategories. These categories are: information, skills, time, equipment, tool, space, material, energy, and general conditions.
3. Performance: its includes properties of a concept that describe of impact construction performance and its classified into two subcategories: results and impacts. Results includes those attributes that describe the performance of the concept such as: cost, production rate, quality and safety. Where the impacts are described the influences on a concept's performance in both direct and indirect and its includes concept complexity (direct impact) and level of automation (indirect impact).
4. External impacts: includes impacts to and from external sources if the concept implemented and its measured based on three factors: environment, adjacent sites and infrastructure.

5. Lessons learned: its includes the lesson learned from similar project conditions and experience, a description of the attempted improvement about such a project, the corresponding results and suggestions for future problem avoidance.

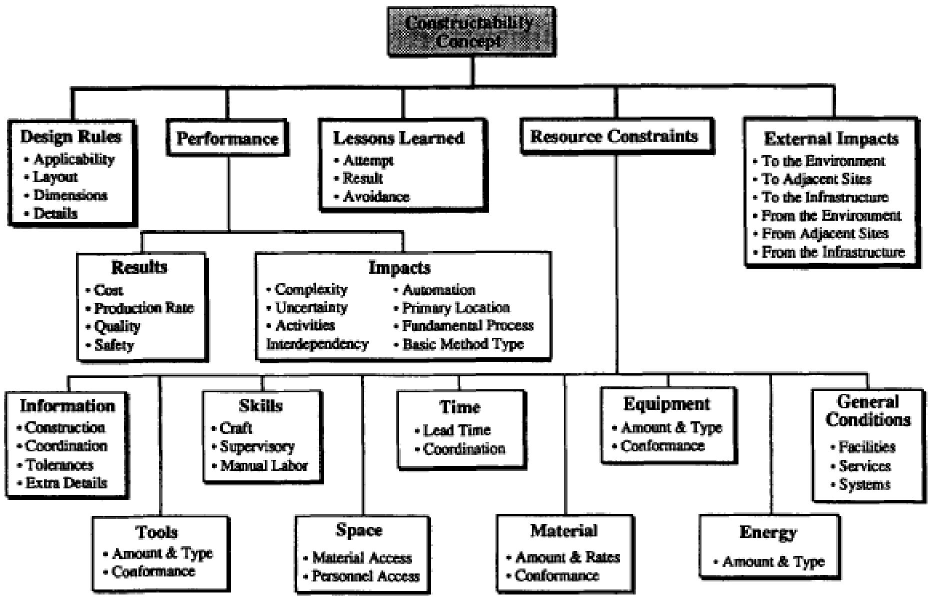


Figure 2. 1: Categories and Attributes of Information for Constructability Concepts

Considering the differences in the phases and the decisions to be made in every project, different constructability knowledge is needed to be applied. (Fischer and Tatum, 1989) outlines constructability factors that capture these differences and they classified them into two groups: factors exogenous to the design and factors indigenous to the design.

1. Factors exogenous to the design: are a data and statistics collected or given for particular project and are considered to be as input or constraints to the design problem. These factors often influence certain construction method applicability and they are out of the designer control.

2. Factors indigenous to the design: these factors such as: core layout, column dimensions and special construction methods) can be controlled by the designer decision directly in the early phases of the design process. This will very likely enhance the constructability of the design and lead to lower cost, reduced time-consuming construction methods and less change orders.

Table 2. 1: Indigenous and Exogenous Factors (Fischer And Tatum, 1989)

FACTORS EXOGENOUS TO THE CONTROL OF THE DESIGN	**Area conditions and resources**
	Site conditions
	Owner's objectives
	Regulatory influences
	Good construction practice
	Type of contract
FACTORS INDIGENOUS TO THE DESIGN CONFIGURATION	Basic configuration
	Preferred details
	Size, quantity of elements
	Modularity
	Simplicity
	Standardization
	Repetition
	Interaction with other function

In the similar manner, (Lam et al. 2006) conducted a questionnaire survey aimed to identify the design attributes that's effects the constructability. The survey showed twenty attributes that effects the constructability and categories under five headings:

1. Site condition: thorough site and ground/underground investigation in the early planning design stage found to be crucial to minimize delay during construction and reduce site conditions variables effectiveness such as: shape of footprint, access as well as properties and facilities surrounding the site.

2. Coordination between documents/components/working sequence: drawings, specification and schematic diagrams along with compatible certainty between different components in the building and sequence of trade are going to ease the communication among builders and allow smooth workflow of construction activities with less time wasting.
3. Standardization and repetition: designing for standardization and repetition would facilitate constructability achievements in terms of the economy of scale, reduced error prone and improve efficiency
4. Safety: constructability implementation in the design stage enhances the safety aspects of the construction progress by providing safer environment for the worker and avoid costly accidents that could affect the credentials from the contractor perspective.
5. Ease of construction: design for simple fixing methods and connection details helps to improve workflow in the site operation.

The early consideration of constructability knowledge during the conceptual design confirmed to be very effective approach to improve project performance and delivered high efficiency in terms of cost, time and safety.

Constructability Implementation and Benefits

The Construction Industry Institute (CII) highlights the benefits of implementing effective constructability program from reducing overall project cost and schedule by 4.3% and 7.5% respectively as well as improving project quality, safety and minimizes rework and rescheduling on the project. All these benefits are always associated with introducing constructability early in the project and continued throughout the design and construction phases as a key for project success. A comprehensive approach to implement effective constructability was developed by CII represents the "Roadmap" for that approach and it's consisted of six milestones as shown in figure 2.2 below.

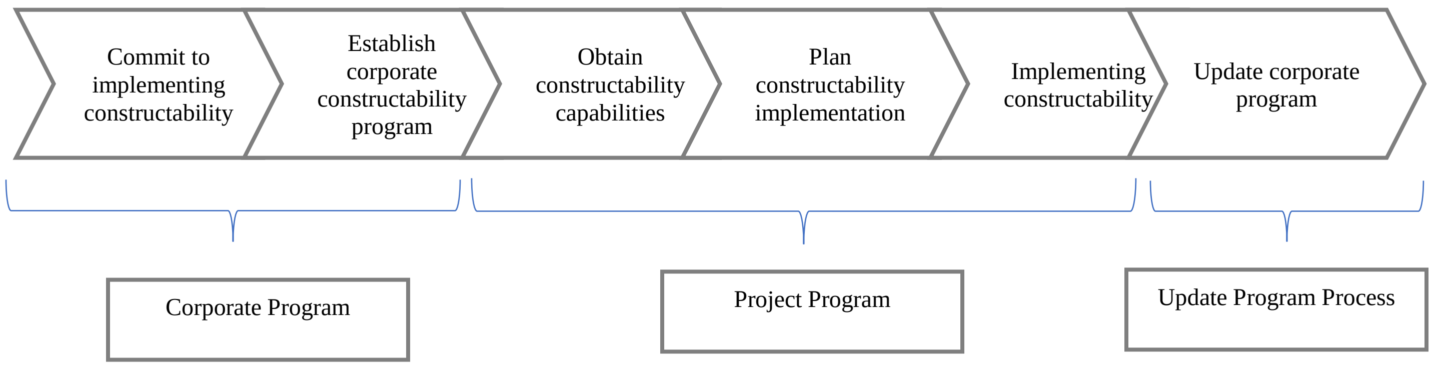


Figure 2. 2: Constructability Implementation Roadmap Inspired by CII 2006

A concept of connecting between the actual constructability functions performance throughout different phases of project development has been studied by (Anderson et al. 2000) by linking between constructability review process (CRP) and project development process (PDP) to demonstrate the interactivity and exchange information process in planning, design and construction phases in project lifecycle as shown in figure 2-3 to achieve effective constructability implementation.

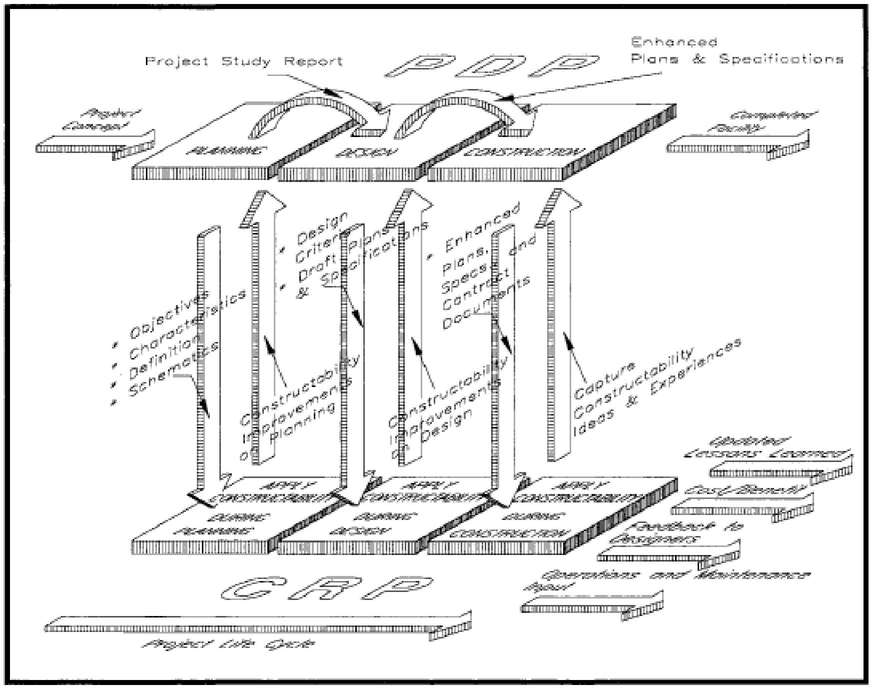


Figure 2. 3: Integration of CRP and PDP

An intensive research has been conducted on 145 articles emphasizes the benefits of implementing constructability concept and 10 benefits identified as illustrated in figure 2.4 (Kordestani Ghaleenoe et al. 2017)

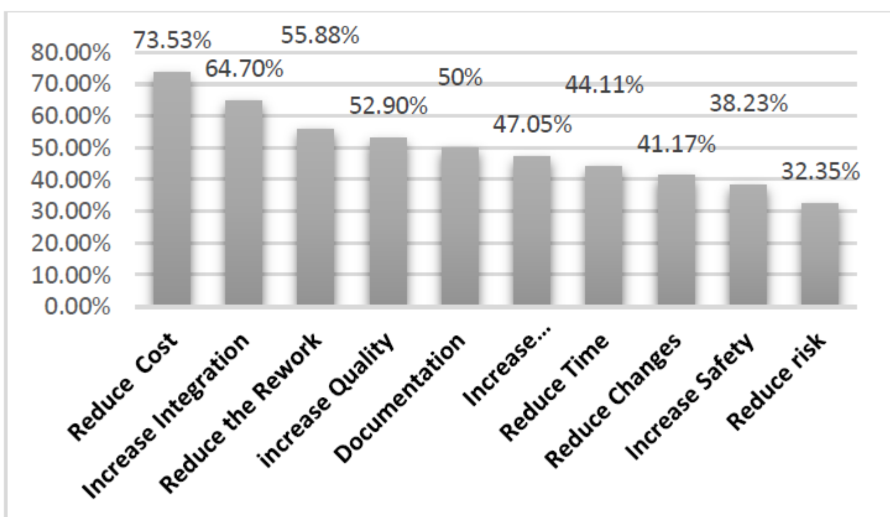


Figure 2. 4: The Benefits of Implementing Constructability Concept Since 1980 Up to 2017

Since the execution of any construction project within the anticipated completion date is highly important to the owner, many design firms approaches constructability review as early as conceptual planning stage to mitigate challenged such as scheduling problems, delays and disputes during construction process (Arditi et al. 2002). As a result, (Arditi et al. 2002) conducted a questionnaire survey design firms to investigate the constructability implementation and its benefits in terms of developing better relationships with the clients, better reputation and efficient design as shown in figure 2-5 below.

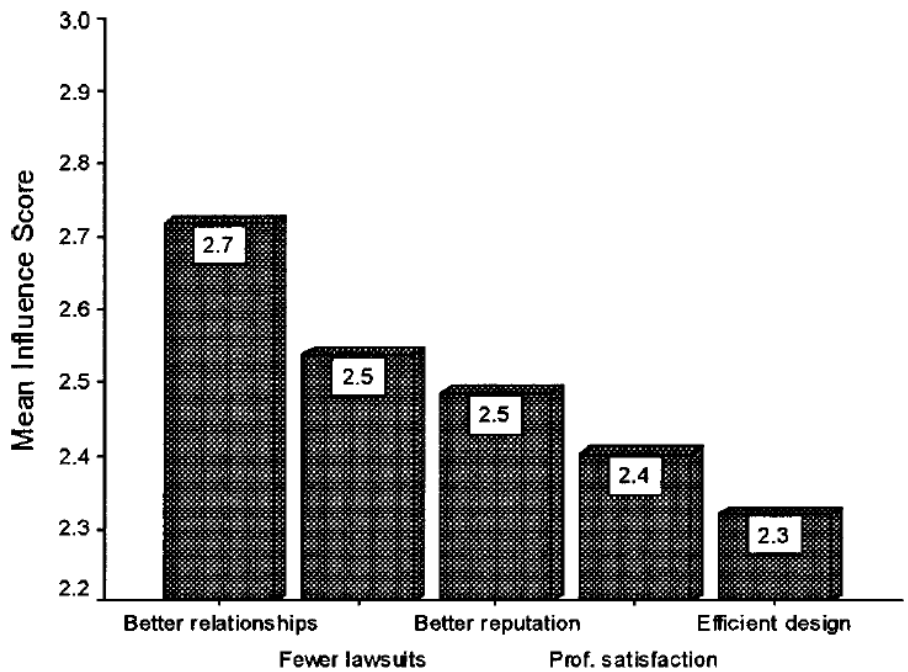


Figure 2. 5: Constructability Benefits

In order to assess the constructability state of practice among architecture, engineering and construction, a survey has been done by (Pocok et al. 2006) on approximately 100 owners, architects, engineers, consultant, contractors, and construction management form across the United

States to investigate the timing of constructability efforts and the mechanism uses to achieve effective constructability. The survey indicates that 83% of the respondents practicing the constructability efforts before construction with 41% in the conceptual design phase. Figure 2-6 provides a more breakdown detail as shown below.

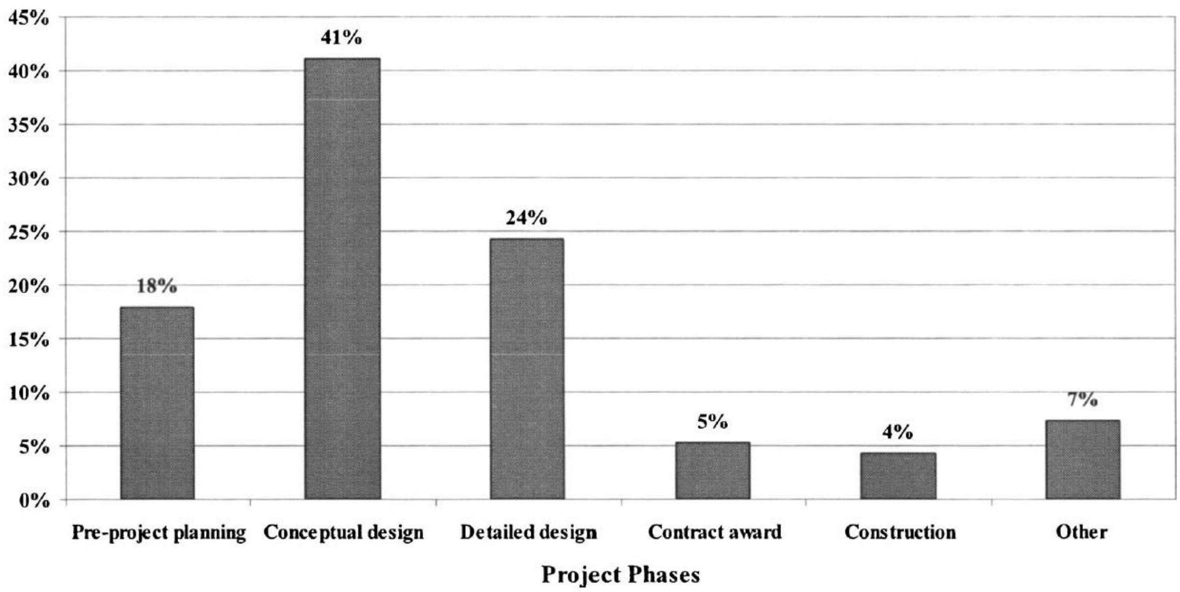


Figure 2. 6: Timing of Constructability Efforts

The current constructability implementation methods offer sufficiently great benefits throughout project lifecycle. However, it's still limited to basic principles in terms of the design review and tools such as construction experts review and checklist which considered relatively unsophisticated reviewing process (Pulaski and Horman, 2005). Moreover, these methods often lead to rework and inefficient construction process represented by either regenerate design documents or preventing project improvement in the jobsite (Pulaski and Horman, 2005). Since the constructability concepts stem on integrating engineering, construction and operation knowledge and experience for effective implementation (Arditi et al. 2002). (Pulaski and Horman,

2005) believes that organizing constructability information provides an opportunity for savings and streamlining projects at every phase of development process by designating level of details needed. As a result, a Conceptual Product/Process Matrix Model (CPPMM) was developed to help designer identify what level of constructability information with correspondent project phases in a timely manner as shown in the table 2-2 below.

Conceptual Product/Process Matrix Model

			Product Model Architecture (Level of Detail)					
			Project	Building/Site	System	Sub-System	Components	Elements
Process Model	Plan	Define Needs						
		Feasibility Studies						
		Program Development						
		Project Execution Plan						
	Design	Conceptual Design						
		Schematic Design						
		Design Development						
		Working Drawings						
	Build	Shop Drawings/ Submittals						
		Construction						

Note: The shaded cells represent an ideal project

Figure 2. 7: Conceptual Product/Process Matrix Model

As shown in the table 2-2, this model is a combination of two models. The first model is Product Model Architecture (PMA) projected by the columns which organizes available data by arranging different building information at each level (Sanvido et al. 1990) and the second model is Integrated Building Process Model (IBPM) projected by the rows which demonstrate activities involved at each project delivery process (Sanvido et al. 1990). While the CPPMM shades area in the table 2-2 pinpoint the ideal interactive between project phase and level of detail and which issues should be addressed, its subjected to the uniqueness of individual project or delivery systems conducted and should be adjusted accordingly (Pulaski and Horman, 2005). Table 2-3 illustrate the mechanism of CPPMM and how different detail levels are defined in it based on each level (Pulaski and Horman, 2005).

Level of detail	Description	Constructability example
Building/site level		
Building/site level	Defines buildings, land, and infrastructure within a facility (roads, electrical utilities, communication, water utilities, gas utilities, lighting, waste removal, and site conditions).	Design buildings to follow the natural contours of the land instead of excavating the land to suit the building.
System level		
Defines selection, sizing, and order of operations of each system		
Architectural systems	Space allocations, net and gross area, finish material types, life safety requirements, energy guidelines, loading restrictions.	Prefabricated smartwall system used to improve space flexibility, reduce, material waste and ease of installation.
Technical systems	Design criteria, code requirements, system types, available fuel sources, power requirements.	Fan-powered induction units allow return air to be taken directly from occupied space thus reducing amount of ductwork by half.
Structural systems	Load assumptions, structural system type, materials available, soil characteristics.	Use tunnel formed cast-in-place concrete in lieu of masonry or precast concrete to reduce labor intensity.
Subsystem level		
Defines subsets of building systems		
Architectural systems	Envelope, floor, vertical connectors.	Provide access to mechanical rooms for maintenance from corridors to eliminate disturbance to tenant space.
Technical systems	Electrical, communication, fire protection, lighting, heating, ventilation, and air conditioning, security, plumbing, acoustic/vibration.	Create specific zones for all above ceiling work in standard areas (e.g., hallways, standard office space) for each discipline (e.g., electrical, IT, security).
Structural systems	Foundation, structure, envelope, roof.	Foundations should be designed as shallow systems (e.g., spread footings) rather than deep systems (e.g., piles) where possible to minimize ground penetration in unknown site conditions.

Figure 2. 8: Levels of Detail on Construction Projects

In conclusion, the maximum benefits of implementing constructability can be achieved by incorporating the constructability review into the project development process early in the planning and design phases. The constructability concepts became a quality indicator among engineers and design professionals and a scale of their final product (Arditi et al. 2002). Many literature studies and practical application demonstrate existence benefits of conducting constructability as a sophisticated approach to achieve optimum project objectives. In order to implement effective constructability review, many efforts have been dedicated towards developing a different tool to help with implementation process. The next section will expand upon the variety of tools developed to execute constructability approach and its limitations.

Constructability Tools

As demonstrated throughout the previous research efforts, a variety of tools conducted and developed in sake of implementing effective constructability process. These tools specifically targeted the structural aspect of the building construction basically because its dictates a big amount of the project cost. This section will expand upon describe and elaborate tools that are considered to achieve efficient constructability with regard of structural system of the building. Two set of tools of constructability review are discussed: (1) knowledge-based systems and (2) quantitative analysis systems.

Knowledge-Based Systems

A knowledge-based system (KBS) is a system that uses artificial intelligence (AI) to support human decision making, learning, and action by incorporates a repository (database) of expert knowledge with utilities designed to facilitate the knowledge retrieval in response to specific queries, along with learning and justification (Akerkar and Sajja, 2010). Steel fabricator and erectors for instance, they can have different point of view for given steel structure (Jiang 2016). A knowledge-based system with connected repository of expert knowledge facilitate organizing knowledge into efficient structure and systematizes the application process (Jiang 2016). "It is more efficient than human experts are and, at the same time, tries to become as effective as human experts" (Akerkar and Sajja, 2010). The knowledge-based systems divided into two categories: non-graphical knowledge-based systems and graphical knowledge-based systems associated with the approach of addressing challenges of achieving effective constructability.

Non-Graphical Knowledge-Based Systems

A repository database is a key element in non-graphical knowledge based systems tool to generate a rule-sets in order to assess and automate decision making process (Jiang 2016). Based on the level of details of constructability input discussed above (Table 2-2 and Table 2-3), five of the constructability tools listed under this category can be utilized throughout the project lifecycle. (Salazar and Brown, 1988) presented a model in the preliminary design of low rise commercial building attempts to automate an integrated approach for the preliminary design of buildings. Incorporate both design and construction knowledge is a way of developing systems to assist designers in the selection and use of information and knowledge during design decision making. High integration of design and construction knowledge can be accomplished by making available small pieces of relevant constructability knowledge at each design step. Another study by (Murtaza et al. 1993) focuses on the decision-making methodology designed for client to evaluate the feasibility of modularized constructability concept in the comparison with conventional one in terms of cost potential saving or increasing in the construction of a petrochemical or power plant building.

In his collaborative research, (Ugwu et al 2005) developed a knowledge formation for constructability analysis of steel frame structures based on the ontologies as a foundation of knowledge-based systems problem solvers. in order to identify the issues associated with managing constructability knowledge, the research explain the business process involving with typical construction project. The process generally commences with client's functional requirements, architect, professionals and fabricators. Thus, generating an intelligent agent utilizes knowledge acquisition (i.e. ontology + rules) to perform as assistant to help decision making process and automatize the evaluation of constructability assessment. Table 2-4 below illustrate a formal structure of knowledge representation for the constructability analysis problem to support organizational knowledge bases.

(a) Holding down bolts

	Standard bolt lengths				
Diameter (mm)	M16-4.6	M20-4.6	M20-8.8	M24-4.6	M24-8.8
300	P, A	P, A	P, A	NS	NS
375	X	P, A, ET	P, A	X	X
450	X	P, A, GB	P, A	P, A, ET	P, A

(i) P: Denotes popular bolts stocked by bolt distributor, (ii) A: denotes other available bolts, (iii) NS: denotes not standard to BS7419, (iv) X: denotes standard available but not preferred, (v) ET: denotes full bond to Exact Theory, (vi) GB: denotes full bond to Green Book [Note "Green Book" is Company ABC's acronym for a standard steel design handbook with a green cover].

(b) Washer plates

Washer plates to theory			
Bolt size	Grade	Washer plate	Proposed column
M16	Grade 4.6	100×100×10	R.S.A./P.F.C
M20	Grade 4.6	100×100×10	203–457 U.B.
M24	Grade 4.6	100×100×10	533 U.B
M20	Grade 8.8	130×130×10	203–457 U.B
M24	Grade 8.8	130×130×10	533 U.B

(i) On an individual project the use of Grade 4.6 and 8.8 HD Bolts of the same diameter should be avoided, (ii) Grade 4.6 bolts should be the first choice; Grade 8.8 bolts should only be used where strength/details requires it, (iii) One form 'G' washer is to be ordered with each HD Bolt, (iv) Provide 2 No. grout holes for base plates over 0.5 m^2.

Figure 2. 9: Design Guidelines for Holding Down Bolts and Plates

Considering the difficulty involved in the manual development of constructability knowledge acquisition, (Skibniewski et al. 1997) described a novel approach to utilize machine learning to develop an automated constructability knowledge based acquisition and demonstrate its feasibility. The study investigates the constructability evaluation (ConEva) of beam element in a conventional reinforcement concrete structural frame of 12-story building. The investigation conducted identifies a collection of attributes and their values to support decision making process and it's classified into eight attributes, seven of them considered as independent attributes and one is a dependent attributes (ConEva). Table 2-5 portrait these attributes along with evaluation values represented by poor, good, and excellent to support final decision.

Attributes (1)	Attribute values (2)				
Reinforcement ratio (ReRa)	Low	Average	High		
Reinforcement ratio of the first beam-to-column connection (CoBeRa1)	Low	Average	High		
Reinforcement ratio of the second beam-to-column connection (CoBeRa2)	Low	Average	High		
Number of attaching slabs (NoSla)	None	One	SameTwo[b]	DiffTwo[d]	
Number of attaching walls (NoWall)	None	One	SameTwo	DiffTwo	
Changes of beam on the first side or left side (BeChal)	None	SlichgeReinf[a]	AllChgeReinf[c]	WDChange[e]	AllChange[f]
Changes of beam on the second side or right side (BeCha1)	None	SlichgeReinf	AllChgeReinf	WDChange	AllChange
Constructability evaluation (ConEva)	Poor	Good	Excellent		

[a]SlichgeReinf = Slight changes in reinforcement.
[b]SameTwo = Same slabs or walls on both sides.
[c]AllChgeReinf = All reinforcements were changed.
[d]DiffTwo = Different slabs or walls on each side.
[e]WDChange = Width and depth were changed.
[f]AllChange = Both reinforcement and size were changed.

Figure 2. 10: Dependent and Independent Attributes for Beam Structural Analysis and their Values

Even in advance design stages, non-graphical knowledge-based systems can be utilizing in the construction planning and method at that stage (Jiang, 2016). Considering the cost effectiveness for a single construction method, formwork selection for instance in reinforcement concrete structure, its dictate 35% - 60% of the cost of concrete skeleton (Hanna et al. 1992). As a result, (Hanna et al. 1992) developed a tool comprises of selection criterion and knowledge acquisition of an expert system to help designer making efficient decision covered the constructability factors involved throughout the lifecycle of the formwork from design through erection and concrete placement to its removal. The techniques uses to extract and create the knowledge base fall under three stages:

1. Familiarization stage: the major goal of this stage is to identify the scope and complexity of the problem domain and to emphasize the determination of the initial objectives earlier in the process. The familiarization conducted and achieved by unstructured interviews between knowledge engineer (KE) and formwork expert (FE). This in turn, will provide a solid base to set up a comprehensive question to initiate more structured interviews.
2. Elicitation stage: this stage encapsulates the extraction knowledge base required to form refined rules and facilitate the task of KE to encode these rules in a selection environment.
3. Organization stage: the purpose of this stage is to generate a comprehensive structured key concepts, rules, and knowledge base that can be transformed into representative scheme compatible for the desired expert system shell. Figure 2-7 shows a condensed form of the knowledge base for vertical formwork system.

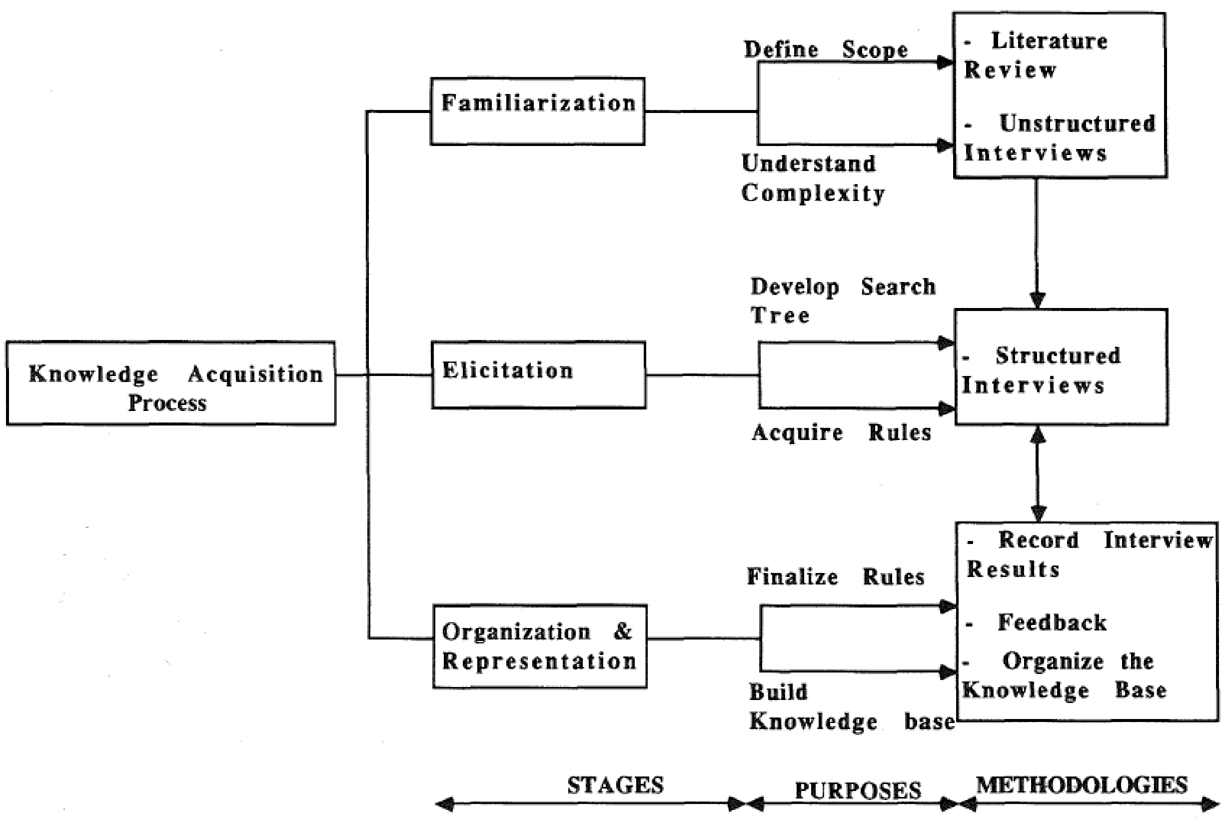


Figure 2. 11: Knowledge Acquisition Process

Despite what the system offers in terms of helping designer and planner select the optimized formwork system, the authors advise and recommends manufacturers contact in some unique situation. Also, recommends specific level of knowledge about formwork selection that the users need to acquire to achieve ultimate goal. Moreover, users advised to run the system multiple times in case of multipurpose high rise building due to different functions and features requirement of each floor which can dictate the selection of ideal formwork for each floor.

Graphical Knowledge-Based Systems

Constructability tool is not limited to build a repository database knowledge, in addition, graphical knowledge-based systems is also an effective tool to overcome constructability potential challenges with wide range of solutions and details (Jiang, 2016). Graphical interactivity and communication among stockholders is more effective in the process of decision making (Golparvar-Fard, 2006). Also, graphical representation considered as a powerful technique to enhance, overtime, finetuning of the data required to efficient decision making process (Jarvenpaa and Dickson, 1988). Considering the lack of interactive communication related to design, fabricate, and erect of the structural system among participants, (Werkman et al., 1990) developed a knowledge-based system called Designer Fabricator Interpreter (DFI) to enable structural designers to designate efficient and economic connection of the structural members taken into account shop fabrication and field erection during design stage. The research implemented through the development of distributed problem solving architecture brings the participants (designers, fabricators, erectors) into interactive and collaborative environment to evaluate, critique, and optimize structural members connection from their perspective.

Many research studies conducted to utilize computer aided design (CAD) as an effective tool in planning and design domain to facilitate constructability implementation efficiently (Jiang, 2016). One of these studies addresses insufficient integration between design and construction of the project lifecycle presented by (Navon et al., 2000). The study investigates the automated rebar constructability diagnosis in the design phase to prevent weaken reinforced concrete element during the construction phase. The diagnosis uses object oriented graphical three-dimensional (3D) model to detect the rebar constructability issues and implemented solutions in correction model and report them to the structural engineers. 3D models developed enables analysis that are difficult to achieve in two-dimensional (2D) drawing, such as collision detection and problems caused by conflicting in the building systems (i.e. drainage pipe and HVAC ducts).

Towards more communication and collaborative environment between fabricators and engineers as a crucial approach for more fabrication cost effectiveness, (Ernst and Roddis, 1994) established a model prototype integrates the knowledge-based expert system and computer aided design drawing to analyze and assess fabrication issues and constructability potential challenges of the steel structure ahead of the implementation on the jobsite. Moreover, and due to fragmentation of the construction industry, (Fisher, 1993) developed a construction knowledge expert system to overcome the uncertainty for structural engineers about the constructability knowledge and provide feedback early at the design stage of the reinforced concrete structure. The system automates the inputs od construction expertise to allow efficient decision making upon the construction method. CAD model utilized to test constructability reasoning in terms of object's attributes, relationships between them and spatial reasoning. Also, system will help determined optimum construction method by conducting comparison approach between data in the model and constructability knowledge to provide pro-active feedback for the designer to interact in a timely manner.

Quantitative Analysis Systems

Based on the past research, quantitative analysis systems considered to be an effective constructability tool along with knowledge-based systems (Jiang, 2016). It allows comparing alternatives, problem solving, and decision making (Anderson, 2012). A comparison approach conducted on different design alternatives will give the designer more insight with regard to efficient and cost-effective alternative which can be essential in the decision-making process. A quantitative constructability analysis presented by (Yu and Skibniewski et al., 1999) measures the feasibility of constructed project utilizing technology performance factors such as construction time, project cost, resources requirement, and the constructed product quality. This study presents a quantitative constructability analysis and generates feedback model based on neuro-fuzzy knowledge-based system for technology performance knowledge acquisition and multi-layer aggregation network (MIANet) for multi-criterion constructability analysis. The adopted system incorporates the manager's preference information throughout variety of utility functions and criterion weight to enable constructor's technology management policy to be imposed in the constructability analysis process by either the assignment of proper weights for the different criteria in each layer of MIANet or the selection of suitable utility functions.

Motivated by the dynamic change of the constructability issues over time and to keep the consistency among reviewers as opposed to single- reviewer approach, (Stamatiadis et al., 2014) utilized a systematic method review process to provide lessons-learned database extracted from detailed documents and quantified the frequency and severity of constructability issues by comment type and category, reviewer, and comment severity. Such a process will help to categories the results of constructability review, analyze the outcomes, and enable design engineers to use them on the future projects as a constructability tools. Another study by (Lam et al., 2007) uses quantitative decision-making technique and analytical hierarchy process (AHP) to identify provide scale of priority to measure the constructability performance of popular construction systems of building super structure. The popular construction systems investigated are structural frames, slabs, envelopes, roof, and internal walls to extract factors that has the most effects on the constructability based on the questionnaire survey. Identified constructability factors indicates high demands for easily visualized and coordinated the design by site staff and enable the participant to adopt and develop alternative construction details.

Similarly, a quantitative analysis approach of the factors that effects the constructability was conducted by (Jarkas, 2010) on edge formwork and its consequences on the labors performing this intensive construction activity. The quantifying analysis investigates the depth of slab, slab geometry, and type of formwork material used (i.e., plywood sheets vs. timber boards) as a major constructability factors that impact the task level difficulty of edge formwork. Multiple categorical regression method implemented on massive collected data related to labors performance to evaluate the influence of each constructability factors. In turn, this study provides designers with a feedback about the satisfactory of their deign in terms of accommodating constructability requirements and the results of implementing such approach. Additionally, its improves the leadership skills of the construction managers towards more effective planning and efficient labors coordination's.

Summary of Constructability Tools

To sum up the constructability tools, the literature review discussed in the previous section emphasizes the benefits of conducting constructability analysis utilizing knowledge-based systems and quantity analysis systems as a substantial tool based on the knowledge acquisition of construction expertise. A set of constructability rules or quantitative analysis on model developed provides an effective construction feedback for engineers and professionals during design stage. Questionnaire survey and interview methods for extract knowledge acquisition are the most useful and frequently applied for that purpose. Reinforcement concrete and steel structural framing design was the main focus of tools discussed. Some of them utilizes labors performance analysis for intensive construction activity with constructability analysis, others leveraging visualization of constructability issues to communicate between parties in graphical-based design environment. However, these constructability tools have some limitation in practice as most of them are targeting specific element of the structural design in particular such as beam and column, to name of few, and construction method as oppose to systematically focusing on discover the constructability issues of the entire structural design to optimize decision making process and achieve constructability objectives. Another limitation that existed constructability tools struggling with is that constructability knowledge acquisition database has to be incorporate as early as possible during design stage. Time effective of constructability knowledge involvement is an important factor to enhance feedback and improve proactive process during constructability implementation otherwise the benefits of utilize these tools will compromised and lead to inefficient design procedure (O'Connor and Miller, 1994).

The process to achieved effective constructability implementation needs to be versatile in order to accomplish efficient review tactic. Visualized and automated capability is a robust approach to gain design related constructability knowledge and ideal to designate constructability issues iteratively and thoroughly to support proactive feedback for design (Jiang, 2016).

BIM and Game Simulation as Visualization Tools

Effective constructability analysis starts at the beginning of the conceptual design phase, along with construction documents preparation tasks. Several approaches have been taken in the past to optimize project outputs in this phase. For instance, numerous companies (especially those in the private sector) showed their shifts from traditional project delivery methods to more integrated project delivery methods, to give all project participants more opportunities to collaborate and communicate, which can benefit many problem-solving processes. Visualization techniques fit perfectly in such collaboration/communications. In the last decade, BIM uses grew drastically in the architecture, engineering, and construction (AEC) industry and drew a lot of attention. BIM is a promising technique because of its interoperability and many other functionalities.

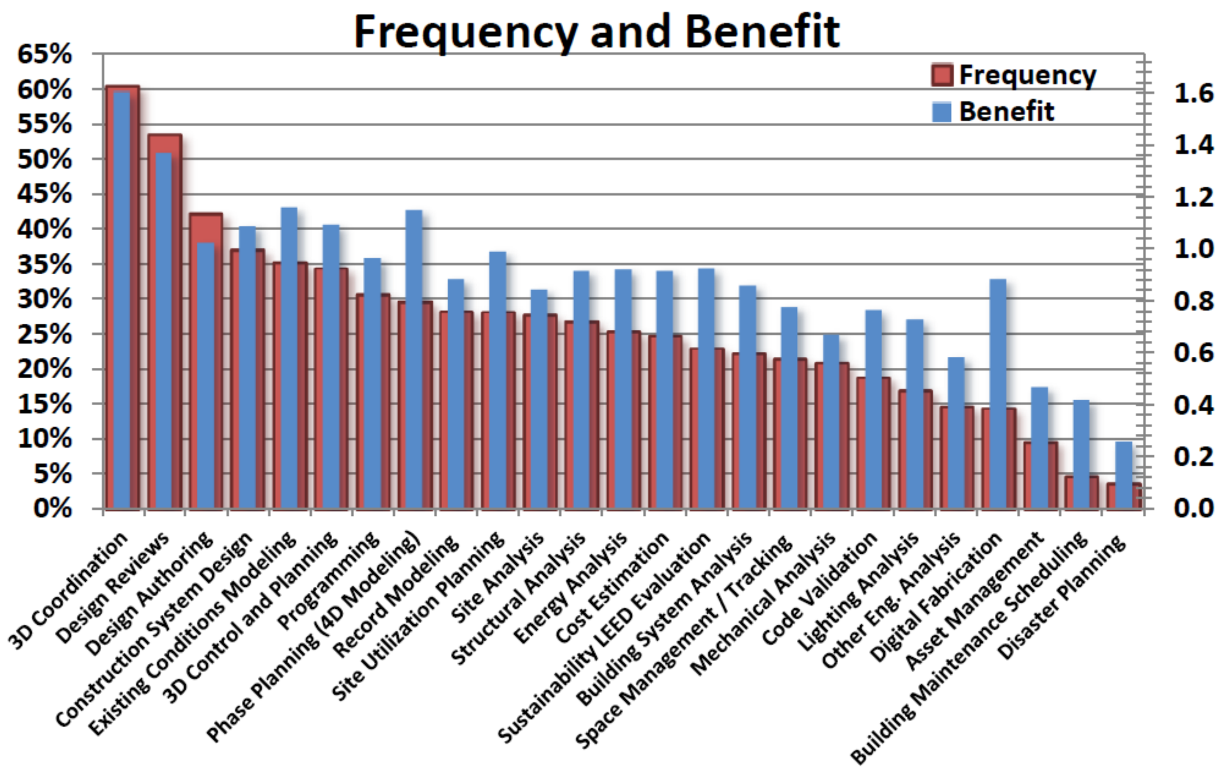


Figure 2. 12: Bar Chart Illustrate the Frequency of Use Each of BIM Use and their Benefits

A survey done by (Kreider et al. 2010) focused on indicating the comprehended advantages of implementing BIM to cover the span lifecycle of construction projects from planning, design, construction, and operation uses. The survey showed that the most beneficial and constantly use of BIM is in 3D coordination and design reviews. It's can be considered as a helpful guidance for the team member to prioritizing appropriate uses for BIM in their projects. Figure 2-8 illustrate the frequency of use each of BIM use and their benefits as shown below.

As defined by National Building Information Model Standard (NBIMS) committee (NBIMS, 2007) "BIM is 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." BIM enables smart virtual architecture design prototyping with embedded transferable information throughout the project lifecycle; this helps ease the collaboration and communication among project stakeholders. Many visualization techniques have been utilized to enhance the communication between parties considering the fact that 90% of the communication time was spent on describing a problem and finding reasonable solutions to that problem (Lee and Peña-Mora, 2006). In this research paper a potential application of metaphor, augmented reality, and color gradients utilized BIM as a visualizing tool to facilitate the decision-making process among parties toward complex construction situations.

Notably, visualization becomes known as a useful technique to support project planners in communication with other people to address potential issues in productivity analysis, manpower coordination, and site layout analysis (Han et al. 2015). Along with the idea in BIM, computer visualization can cover the whole lifecycle of a project from the very beginning of the project to the final stage. The 3D model information can also be used in accessibility and maintainability checking during the design stage, which can facilitate progress towards the construction phase of the project (Bouchlaghem et al, 2005). The abundant computer-based visual representations of activities in the visualization can be utilized at both the design and operational levels, to help with field construction and planning/control processes (Kamat et al. 2011). Furthermore, many compatible techniques of computer visualization can enable a high level of collaboration between construction team members. For example, by adding interactive-dynamic User Interface (UI) to a 3D model, the visualization would allow immersive experience in virtual reality (VR) simulations, which can be used to experience and examine construction activities in the virtual world to predict/prevent potential challenges. VR is a method of visualization using computer technology to generate immersive simulations in interactive way. This method allows the user to move around in the artificial world and interact with the items in simulation, which gives the user a presence sensation very similar to the presence in the real word.

In (Castronovo et al. 2014), User Interface (UI)-based visualization mechanism was mentioned as a necessity for overcoming the lack of collaboration between construction and design phases. Considering the unique UI for each visualization tool it terms of standards for viewing and navigating as well as representing building elements and tasks, (Castronovo et al. 2014) developed a set of guidelines for better illustration of construction process based on the interview approach conducted on Architects, Engineers, and Contractors (AEC) professionals and experts as the end user and their recommendations

Table 2. 2:Visualization Guidelines for UI Elements (Castronovo et al. 2014)

ELEMENT	GUIDELINE
Color	• Use color schemes for 3D elements to dictate the activity type and progression. • Use color-coded legends as visual cues. • Utilize color saturation to distinguish object selection.
Lighting	• Use shadows and luminance difference to distinguish highlighted elements.
Transparency	• Use transparency to distinguish importance. • Use various levels of transparency to dictate the status of the activity.
Graphical Quality	• Use anti-alias visualizations wherever possible. • Avoid patterns that can lead to aliasing problems.

Recently, both technologies have drew much attention in the construction industry; because their application allows examining a project in an intuitive, interesting, and effective way to identify potential challenges as early as possible, which in turn allows pro-active measures to be incorporated into better planning/design decisions.

BIM provides a digital representation of physical and functional characteristics of a facility making the creation of visualization experience and simulations for architecture design a lot easier and expediting the construction and planning progresses holistically. However, it is still lagging in terms of creating an interactive visual experience to support pro-active feedbacks and effectively involving participants with significative and programable interactive visualization by leveraging the incorporation of BIM and game simulation to enhance communication and collaboration for design purposes (Wu and Kaushika, 2015). From that point of view, game simulation combined with BIM technology may tackle such a lack of interactive visual experience in a construction project. This combination may satisfy construction industry needs by generating parameterized 3D visual models featuring interactive experience in a virtual environment. Such interactive experiences would allow for a high level of communication and collaboration between project stakeholders. For example, they may perform certain tasks in the artificial world first while observing certain construction operations in real time, to raise issues pro-actively.

Through literature review, Unity3D game engine was identified as a widely-used tool in simulation and visualization researches. It served well the purpose of developing interactive experiences and had interoperability with multiple 3D computer aided design (CAD) and modeling software (e.g., AutoDesk 3ds Max, Maya, and Blender). It allowed animation editing and control, and made easy the addition of physical properties to objects to mimic real world conditions (Wu and Kaushika, 2015, Kumar et al. 2011). This paper attempts to leverage BIM and game simulation technologies in supporting constructability analysis. A visualization method built on these technologies is expected to: (1) help sharing construction knowledge effectively; (2) help decision makers take actions in a timely manner; give workers insight about the work that they are dealing with so as to raise their awareness of various issues in the field operation environment. All these benefits ultimately lead to improved overall project performance towards achieving the project objectives.

Many efforts have implemented virtual simulation for the sake of visualizing and simulating architectural design to support field construction operation and project management. Motivated by the validity that the lift engineers and project managers encounter with regard to design a collision-free crane operation before initiating the construction activities, a study by Han et al. (2015) to simulate feasibility of crane lifting paths to identify and analyze the potential collision accurately to support better communication, collaboration and decision making among stockholder effectively. A methodology proposed to generate a dynamic graphical representation of three-dimensional (3D) visualization to simulate and examine different scenario of crane type and other input and criteria in order to optimize crane operation and facilitate better collaboration and decision making in timely manner as shown in figure 2-9.

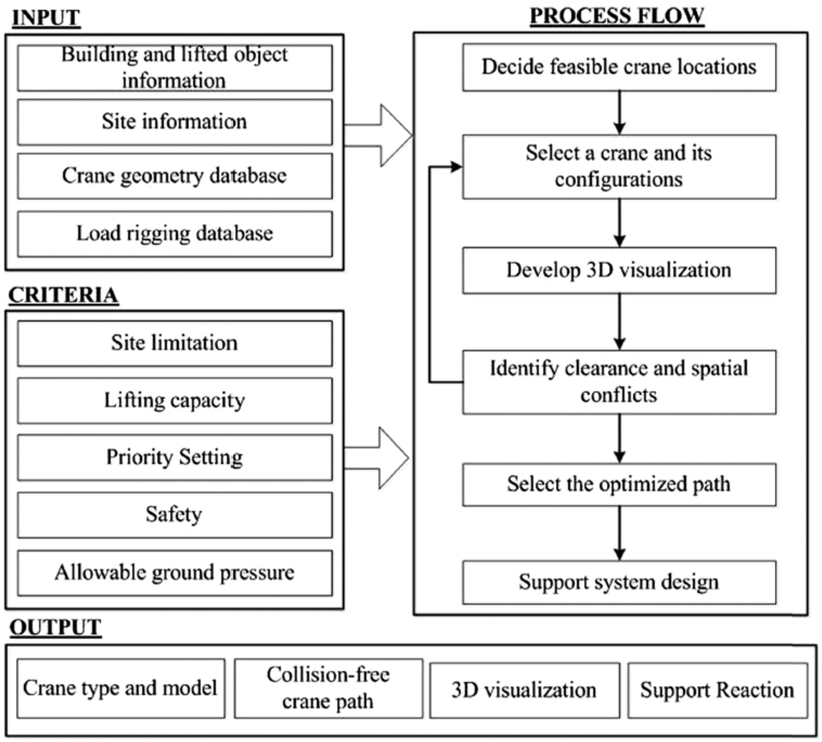


Figure 2. 13: Methodology Proposed by (Han Et Al. 2015) of Lift Planning

Another study was conducted to describe the practical benefits and implementation of 3D visualization of tower crane operation such as assisting decision makers and examine different alternatives based on verification and validation of simulation results (Al-Hussein et al. 2006). A special purpose simulation (SPS) and 3D visualization integrated into practical methodology of tower crane operation on new civil and environment engineering building at University of Alberta to enable domain experts to analyze simulation results. The integrated system utilizes 3D Studio MAX environment. Figure 2-10 and figure 2-11 demonstrate system components and information flow diagram respectively.

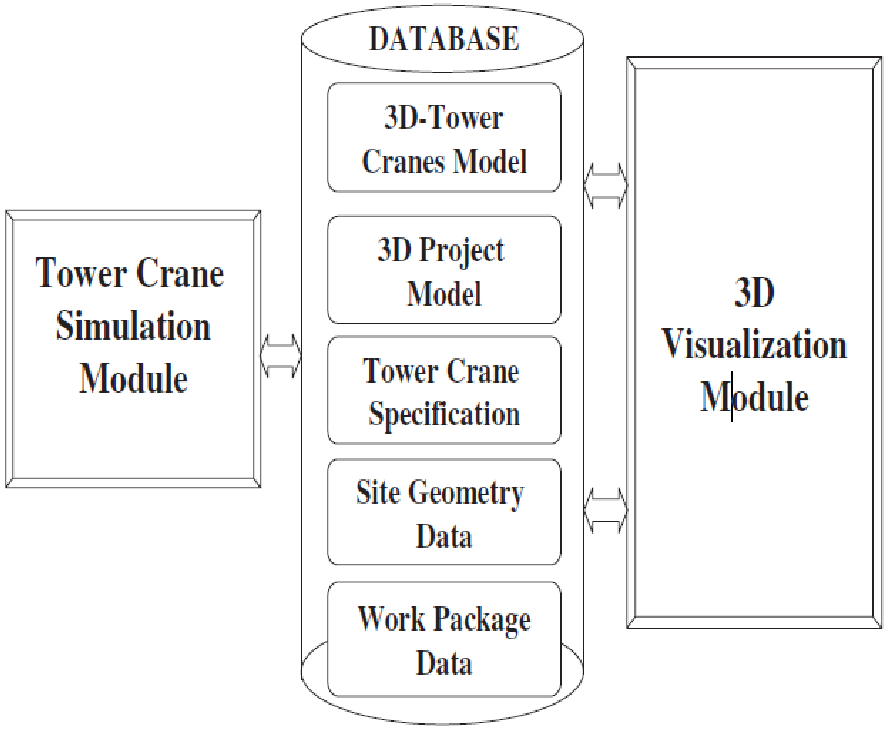


Figure 2. 14: System Components

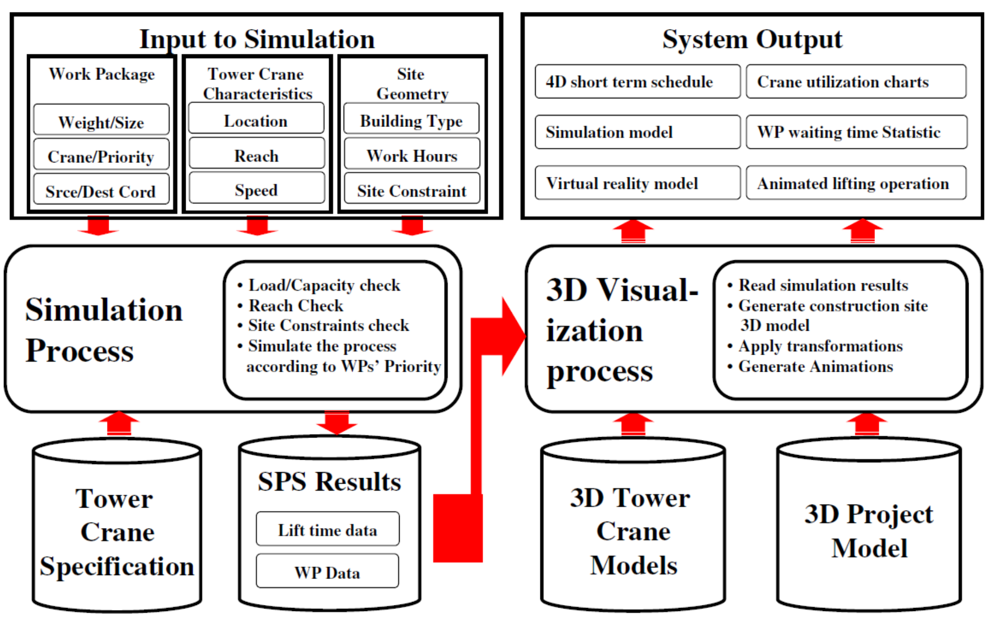


Figure 2. 15: System Information Flow Diagram

Moreover, BIM visualization and simulation technologies applied effectiveness in safety planning and management and renovation projects by generating dynamic simulation allows AEC to visually identify potential challenges in the jobsite (Azher 2017). Additionally, visualizing and simulating construction process are powerful tools in construction management, spatial conflicts and preconstruction studies can be absorbed by participants quite easily, enabling them to solve problems and enhance proactive feedback (Rohani et al. 2013).

BIM with a combination of game simulation gives the 3D visualization more depth by adding an interactive feature which enables users to control visualized information and observe the results of changing this information, this concept drew the attention of researchers in a variety of disciplines. From construction industry point of view, Guan et al. (2013) utilized the use of interactivity feature and 3D dynamic visual scene of high arch dam construction to support site management and decision making by allow the users to observe and analyze the construction process in real time. From a design stand point, Kumar et al. (2011) developed a virtual prototype for a healthcare facility accommodates the interactivity feature that allowed the stockholders (nurse, patient and facility manager) to collaboratively review the design in the virtual environment-based experience and evaluate how the activities structured and connected to each other functionally. Figure 2-16 shows the system architecture of utilizing BIM and game engine to improve the design aspects leveraging the interactivity feature and testing different scenario.

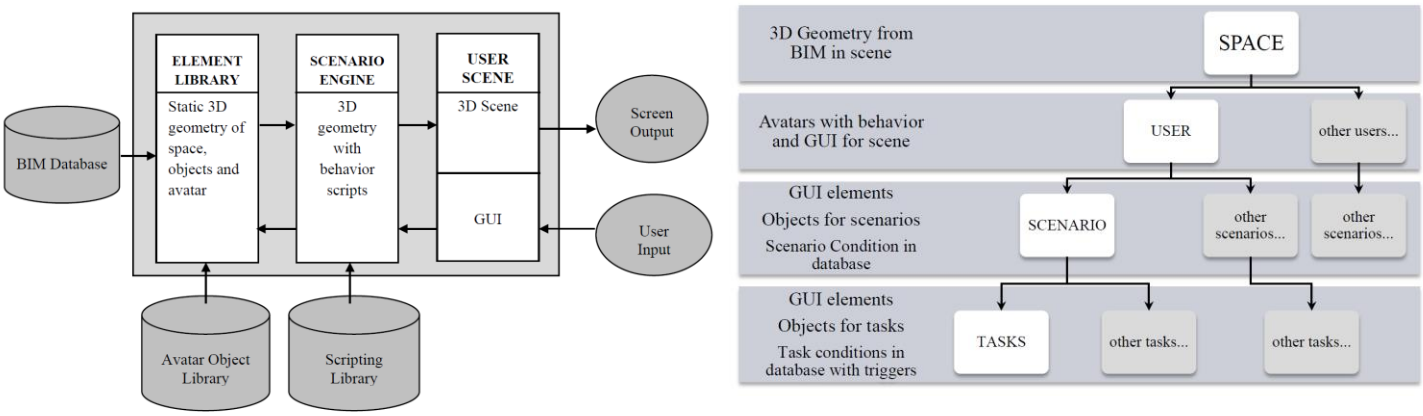


Figure 2. 16: System Architecture

Apart from the implementation in construction and design industry, many efforts have been invested in generating simulated visualization and how to interact with it in the academic field and building science education. Goedert and Rokooei (2016) studied the use of simulated environment and virtual learning to improve students engaging and assessment of civil and bridge engineering by developing a virtual interactive construction education (VICE) to improve users understanding of real world experience context. Figure 2-17 illustrate the user interface of activities sequence for the single span bridge being simulated, also shows the user avatar (student) and consultant avatar to provide guidance at the player request.

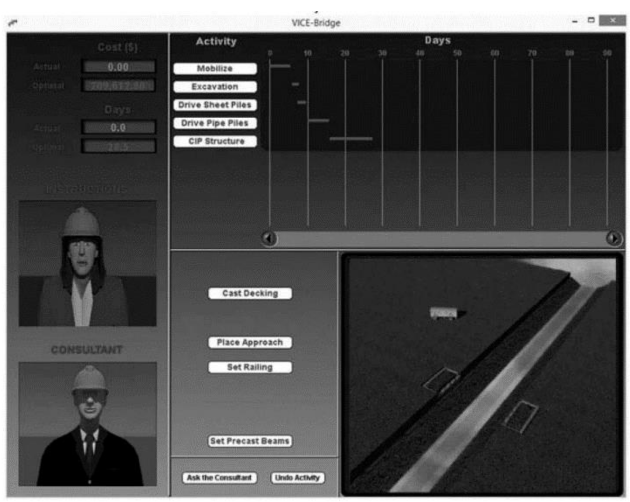


Figure 2. 17: Interaction Phase of Single Span Bridge Simulation

Moreover, and motivated by the importance of user behavior and modeling outcomes, Harman (et al. 2016) conducts and empirical investigation to compare different user behavior in the 3D virtual model of the airport. The model tested on 66 individuals and the results shows that virtual worlds improves knowledge extraction and elicitation as well as enhances quality analysis to be performed. Figure 2-18 is a screen shot captures of the airport in the virtual world with first person controller.

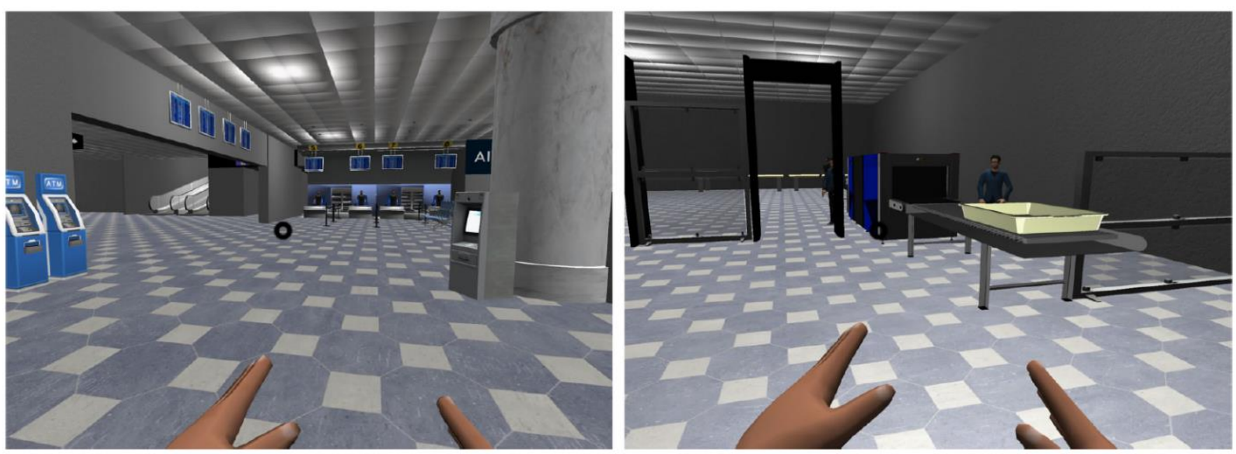


Figure 2. 18: Screen Shot Captures of Airport with First Person Controller

BIM as a Constructability Tool

BIM offers a set of circumstances to facilitate constructability implementation by leveraging its futures from collaboration, communication, and exchanging knowledge and information among participants as early as planning stage. However, BIM have not fully utilized in the implementation of constructability analysis in real world (Jaing, 2016). Exploratory research conducted by (Fox and Hietanen, 2007) on 20 organizations ranging between owners, design consultants, producers, contractors, and software companies to determine the usability of BIM within these domains. The research revealed three effects categories: automational effect, informational effect, and transformational effect. Along with the visualized simulation, the impact of implementing BIM on the constructability analysis can be tremendously beneficial in many field as discussed below:

1. Visualized simulation: in contrary with discussed constructability tools, BIM facilitates engaging of owner, architects, engineers, and contractors effectively in the collaborative environment due to its robust visualization capability and 3D virtual representation. Conducting BIM is highly recognized in the construction industry as a tool to solve constructability challenges and support decision making process (Jaing, 2016).
2. Automational: indicates the work efficiency value derived from the impacts of other factors such as productivity improvement, labor saving, and cost reductions (Fox and Hietanen, 2007). The automational achievement manifested by an automated checking process and analysis conducted by participants using appropriate BIM software instead of manual checking. The automated checking process considered to be more organized, inclusive, and cost effective (Jiang, 2016).
3. Informational: its facilitate decision making bestability throughout thoroughly exchange and process the information among parties utilizing BIM (Fox and Hietanen, 2007). With BIM interoperability characteristics, the information built-in BIM model ease the extraction process of these information and analyze issues associated with the design early in the planning stage and act proactively to achieve constructability objectives (Jiang, 2016).
4. Transformational: its refers to the ability of enhancing reengineering processes and redesigned structures by role changing within BIM (Fox and Hietanen, 2007).

Summary of the Literature Review

In conclusion, from the constructability visualization, BIM, game simulation point of view discussed in the literature review, the contextualizes content for this research is presented. Considering visualization technique and based on the literature review, a set of recommendations need to be taking into account to achieve effective constructability analysis are composed below:

1. Investigate existing techniques thoroughly and examine the possibility of future improvements. Since the implementation of effective constructability dictated by the level of collaboration and sharing knowledge, information, and experience among participants. Therefore, BIM visualization technique and interactive feature that the game simulation offers can satisfy a high collaboration environment requirement in early design stages to conduct the constructability analysis successfully. For that purpose, A case study experiment was conducted on visualizing the erection process of a steel structure to facilitate the understanding of needed construction operation.
2. Develop visualized simulation to illustrate the constructability process in virtual world that mimicking the one in real world based on discrete-event simulation and define the input needed such as time and resources along with proactive feedback to support decision making process in timely manner.
3. Evaluate the contribution of constructability visualization approach in the field operation environment and how such an approach enhances worker's awareness to perform their tasks efficiently.

CHAPTER 3

Research Methodology

The literature review demonstrated the potential benefits of utilizing BIM and game simulation to facilitate the visualization of constructability process and its assessment. Based on that benefits, this chapter expand upon the research process and methodology conducted to develop visualized simulation illustrate the constructability process of steel structure element (column) in the field operation environment in an interactive way. The visualization expected to explicitly captures the relationships between operation field resources and proactively enhances the decision-making process, knowledge sharing, and awareness raising as early as design stages.

Research Procedure

The main research objective was to develop a realistic interactive simulation for constructability analysis to increase and support collaboration between project participants at the planning stage. The research extent was restricted to investigate the potential of the proposed visualization method and to observe what possibility can be achieved on AEC in both office set and jobsite environment. The research procedure is demonstrated and discussed in more detail in the subsequent sections and illustrated in figure 3-1 below.

Investigate Existed Approaches

At the very step of this research, an in-depth literature review was conducted to identify potential challenges and explore the feasibility of visualizing the constructability of steel structure erection process. Building information modeling (BIM) and game simulation utilizes to facilitate the generation of interactive visualized simulation alternatives in the field operation scenario to help decision makers develop their decision with regard to constructability analysis early at the design stage. The preliminary investigation of the visualization technique provides solid theoretical foundation about developing visualized simulation approach for constructability analysis purposes.

Knowledge Extraction

This step encapsulates the process of extract and capture the knowledge with regard to constructability as a fundamental of visualized constructability analysis. The constructability knowledge obtained by exploring discrete-event simulation for similar construction operation targeted in this research. This discrete-event simulation will be the road map for the constructability visualization process and a predefined rule to organize the relationships between resources (workers, equipment, and materials) at the job site which are the basis of the visualization development at the next step.

Visualization Development

After demonstrating the knowledge extraction, the research procedure switched to develop the visualized simulation for the constructability of column steel structure element. Based on the knowledge extracted from previous step, this step in turn dedicated to apply knowledge obtained in a virtual world. The visualization uses BIM and Unity3D game engine with enabling interactivity feature that the Unity3D offers represented by Graphical User Interface (GUI). As indicated in the literature review, these tools are very efficient to generate immersive visualized simulation experience which apparently improves the constructability approach conducted, enhances proactive constructability feedback in a timely manner, and supports effective field construction operation.

Going back to the virtual world preparation, a series of steps need to be done to mock-up the real world environment. These steps divided into five major categories:

1. Generate prototype model: for the purpose of this study, a three dimensional (3D) model with four story building structure generated using Autodesk 3D Studio Max (3DS Max) software before its exported to Unity3D. In Unity3D, couple subsequent steps processed as a part of the visualization configuration such as adding materials, identify the structure element (column) need to be installed, and situate the overall prototype model in the virtual world environment.
2. Provide resources: this step comprises the resources such as workers and equipment required to perform the installation of steel structure column in the virtual world. These resourced imported in the 3DS Max as a block models in order to be configured for massive animation development. This animation produced to reflect the dynamic interactive movement of the resources to perform the installation of the steel column in the virtual world environment. As s final configuration in this step, the models (workers and equipment) along with animation produced exported into Unity3D as an asset and assign materials as well as situate them in the Unity3D environment.
3. Apply physics characteristics: as one of the powerful attribute that the Unity3D has is physics applicability. This step is very crucial to validate the feasibility of performing such a construction operation in the virtual world (Unity3D) environment. Physics characteristics and properties need to be apply on each component in the Unity3D environment to matches the real world environment conditions. These physics characteristics are as following:

- Rigidbody: it’s a component assigned to each moving game object to allow get effected by physics such as falling under gravity and enable adding other physics properties such as mass, drag, and velocity. A rigidbody component is required for any physics based interaction and without it the game objects (column, workers, equipment) will simply hover in midair.
- Collider: is a component that allows the game object they are attached with to react to other colliders of other game objects. It makes the collision occur between the game objects in a realistic way. For instance, if the column falls down while it's been picked by the tower crane it will fall because of the gravity and will collide with ground and bouncing as it should in the real world.

4. Resources behavior's control: after generating all models that are required to perform the construction operation presented in this research and export them in to Unity3D environment as a game objects asset, these game objects must be under control in terms of movement and interaction. To achieve that, a major scripting using C# and Java Script (JS) programing language conducted on each game objects to give the user the ability to control them during the simulation.
5. Graphical user interface (GUI): this step accommodates user interface that allows for interaction through graphical icons or visual indicators. This feature enriches the visualized simulation by making the content more informative. For instance, if the user picks the game object (the steel column in this case) this action will be indicated on the GUI and the status of the game object will be shown on the screen.

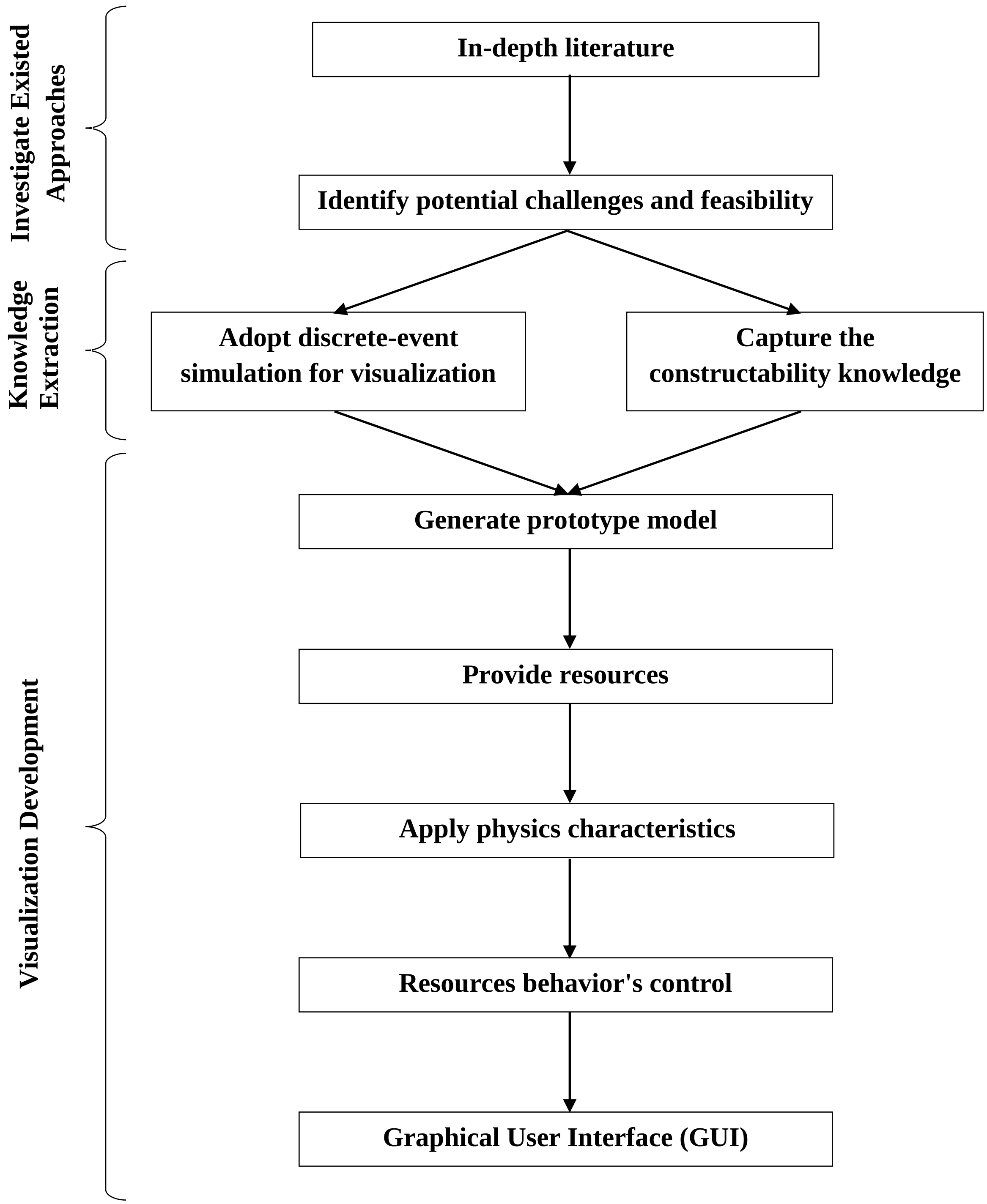


Figure 3. 1: Overall Research Procedure

Summary of the Research Methodology

The research procedure and methodology are utilizes to accomplish a comprehensive research structure to investigate and demonstrate the process of facilitating BIM and game simulation engine to generate a realistic visualized simulation with necessary information needed to achieve this purpose. Three major stages were used to support research methodology: investigate existed approaches, knowledge extraction, and visualization development. Subsequent steps with regard to configuration and development also demonstrated and discussed to improve final product quality in term of the visualization and instructiveness to better serve the constructability analysis.

CHAPTER 4

Research Experiment

Following from above discussions, the main scope of this research is to propose our visualization method for constructability analysis, based on BIM and game simulation. To test the feasibility of the method, it was applied to a case study to visualize and simulate the erection process of a steel structure to analyze constructability in an interactive way. This research shows how such an approach can help decision making, knowledge sharing, and field operation awareness raising. Along with the proposed research methodology in the previous chapter, this chapter will demonstrate the implementation of this research framework on a prototype three dimensional model to support constructability visualization. The prototype model is a three story steel structure commercial building with a concrete spread footing (figure 4-3). This model utilizes to illustrate the achievement process based on the method visualization workflow and system architecture shown in figure 4-1, 4-2 below. The visualization workflow comprises of five steps: (1) models processing and visualization to generate a prototype steel structure; (2) interactive visualization by enabling Graphical User Interface (GUI) feature; and (3) visualization assessment from a decision-making standpoint.

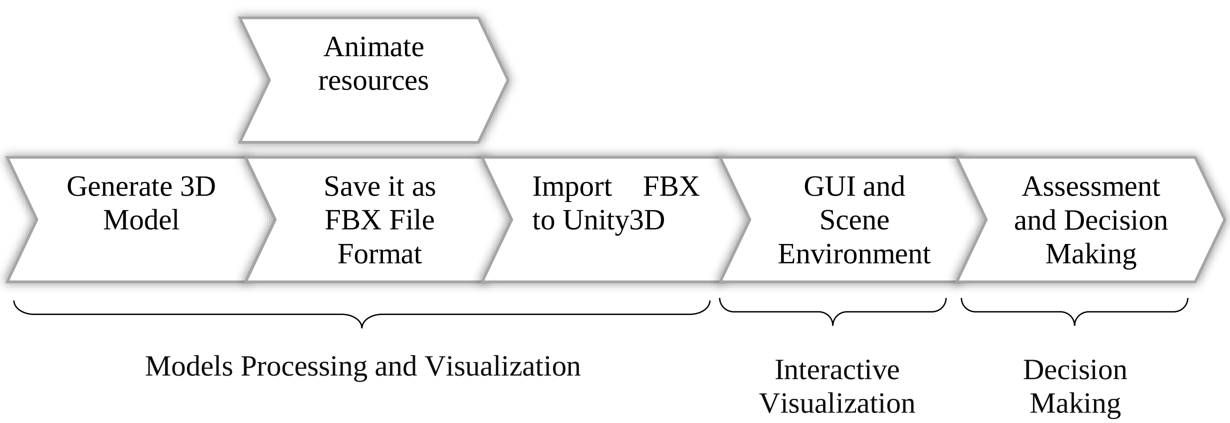


Figure 4. 1: Visualization Workflow

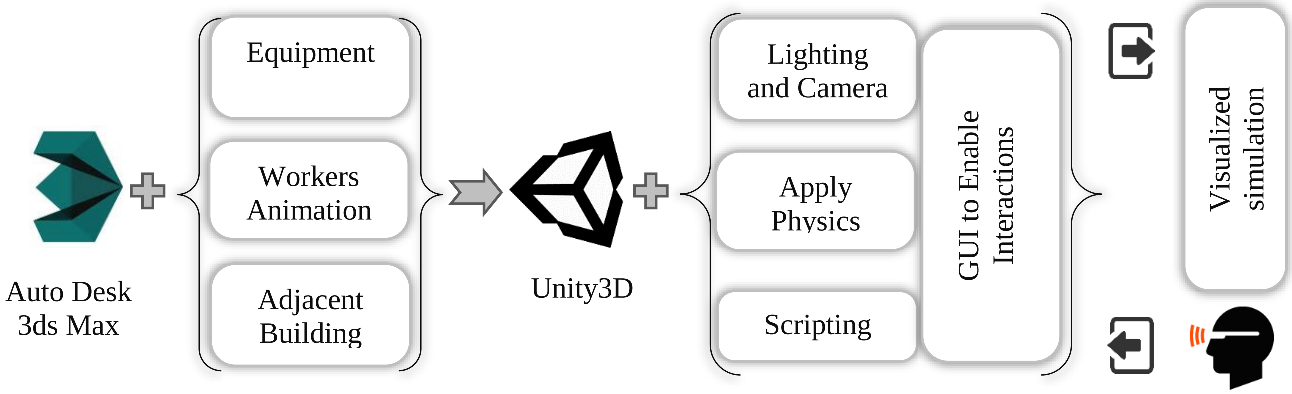


Figure 4. 2: System Architecture

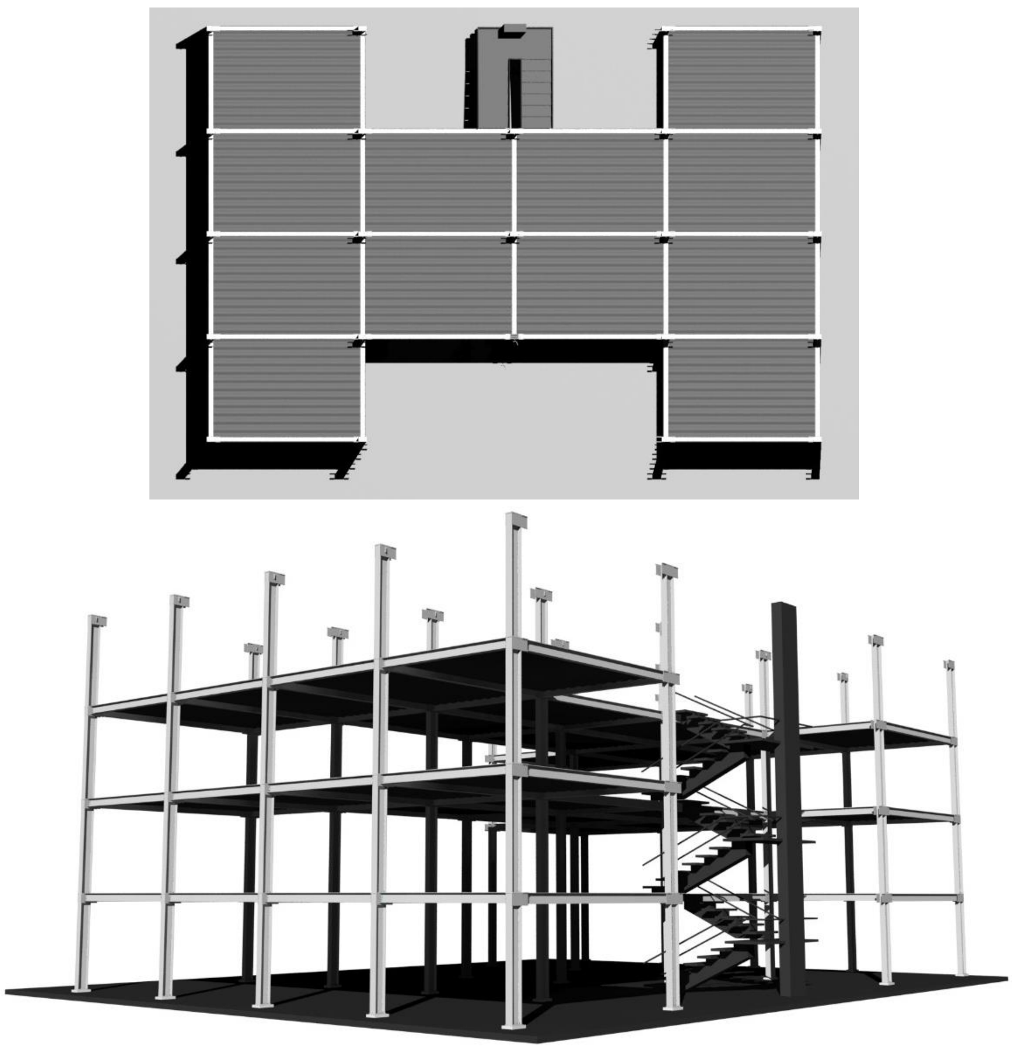


Figure 4. 3: The Prototype Model (Top and Perspective View)

Implementation Procedure

As illustrated in the visualization workflow and based on the methodology procedure discussed in the previous chapter, the implementation process to achieve constructability visualization is rely on the following parameter:

Models Processing and Visualization

The visualization and game simulation applied in this research uses 3DS Max and Unity3D as an efficient tool to generate models to perform the steel column erection process in the virtual world. The models are the basic element for that matter, which involve, workers, tower crane, and prototype building and figure 4-4 depicts resources models in 3DS Max.

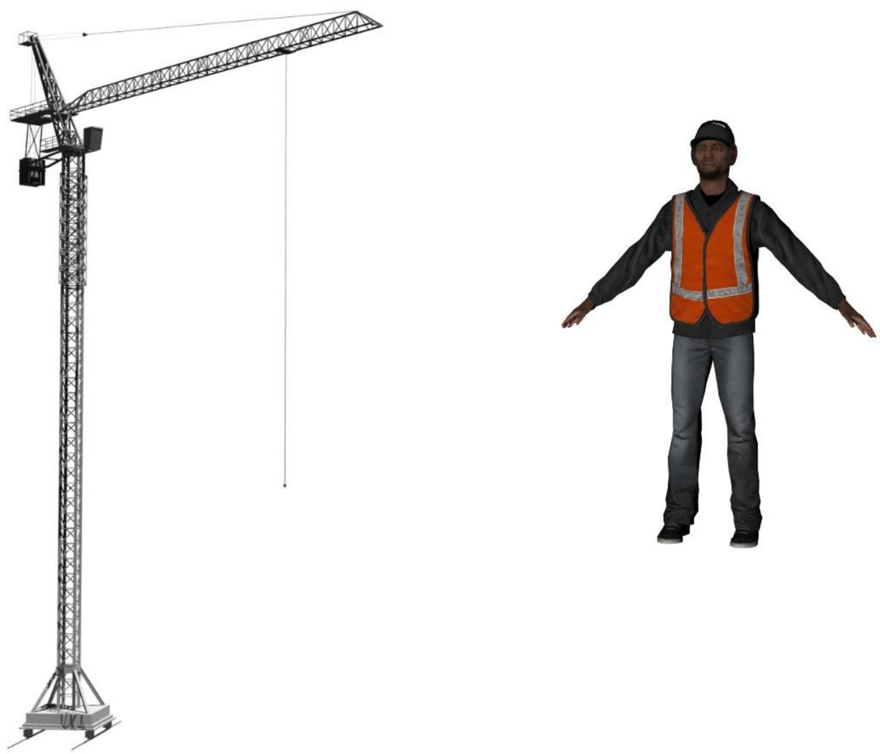
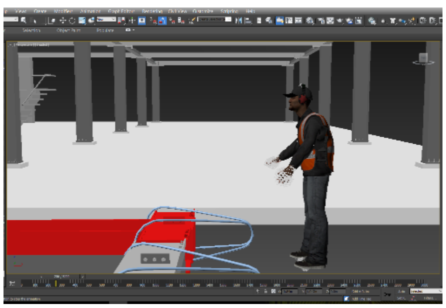
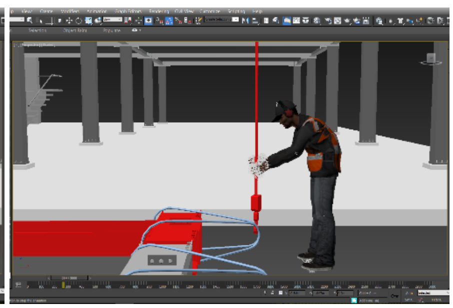


Figure 4. 4: Models of the Resources Used in the Visualization

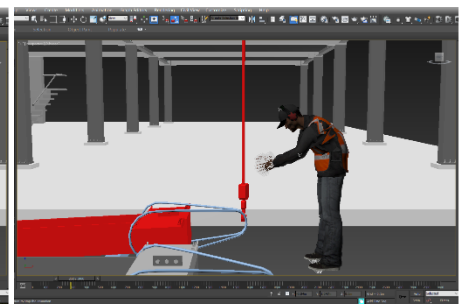
After having all necessary resources models in the 3DS Max, the workers models in particular need to be animated as a humanoid aviator to perform a humanoid animation. An animation clip recorded inside 3DS Max using key frame slider based on the animation data represented by the workers movement in the real world in order to export the animation later into Unitey3D game environment. The key frame slider is recording the animation based on the number of the frame per second (FPS) which can be very useful to generate more realistic visualized simulation. Figure 4-5 illustrate the process of generating the animation clip.



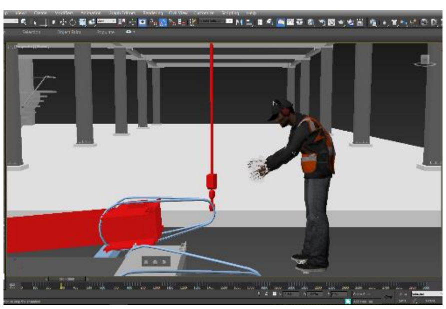
(1)



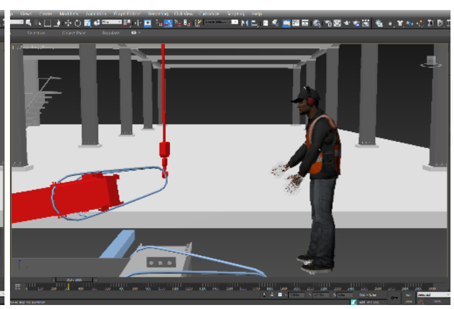
(2)



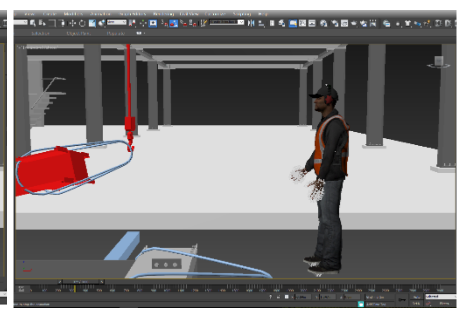
(3)



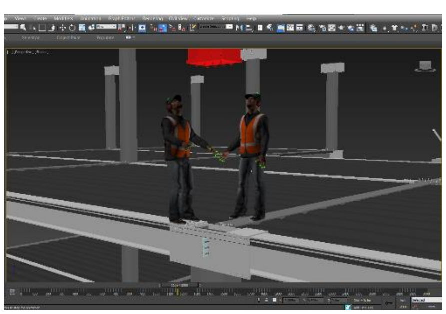
(4)



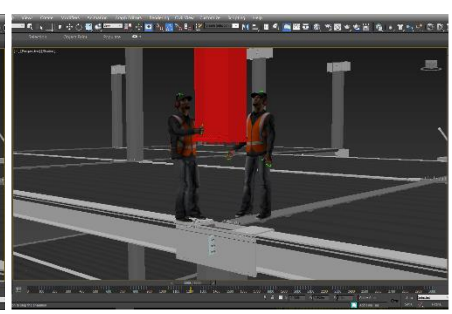
(5)



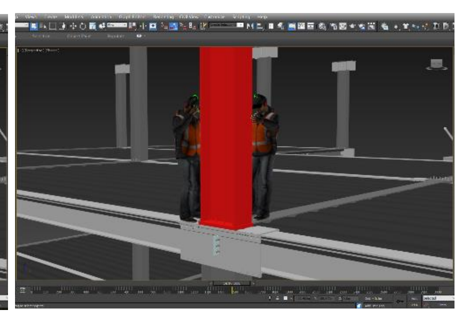
(6)



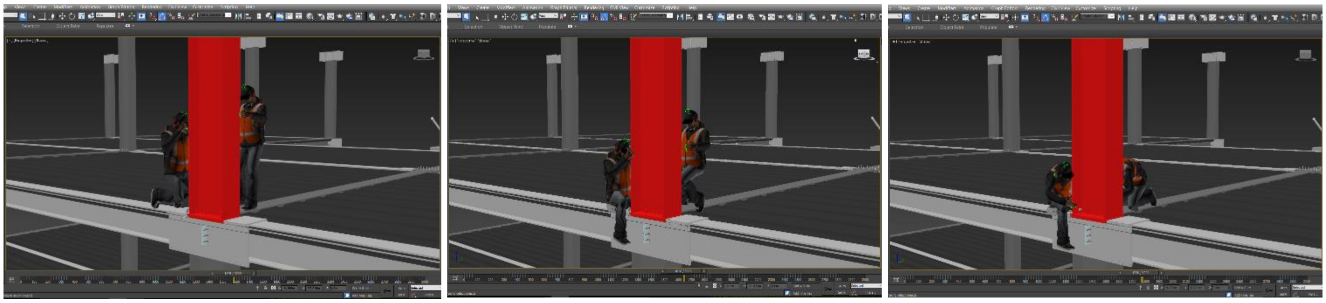
(1)



(2)



(3)



(4) (5) (6)

Figure 4. 5: Illustrate the Process of Generating the Animation Clip for the Workers Attaching Hook to the Column and Installing it

At this point, all resources models along with the animation clip need to be imported and situated in Unity3D game environment as well as adding material on each model as shown in figure 4-6.

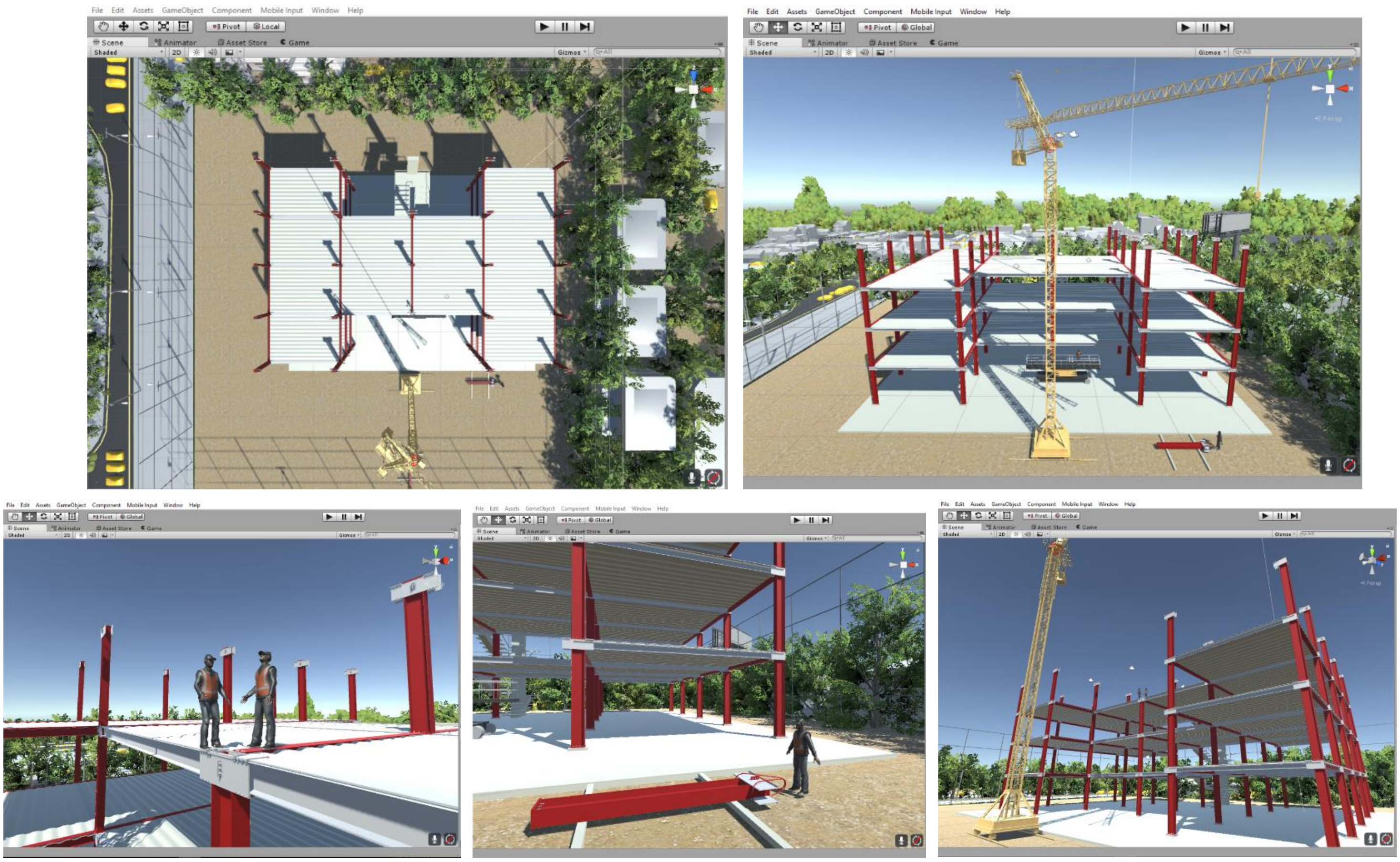


Figure 4. 6: Illustrate the Overall Prototype and the Resources in the Unity3D to Start the Simulation

Considering the dynamic nature and correlated relationships among resources involved in proposed construction field operation targeted in this research, the development of the visualized simulation in this research established based on the discrete-event simulation approach. Adopting discrete-event simulation facilitates the field operation management systematically by offering a thoughtful path which can be very helpful to produce a mature visualized simulation (Kamat et al., 2011). Figure 4-7 shows the discrete-event simulation presented in (Kamat et al., 2011) and adopted in this research as a scientifically proven method to support the resources interactivity in the field operation task. More detail about implementing discrete-event simulation concept will be tangibly recognized and holistically pictured in the visualized simulation.

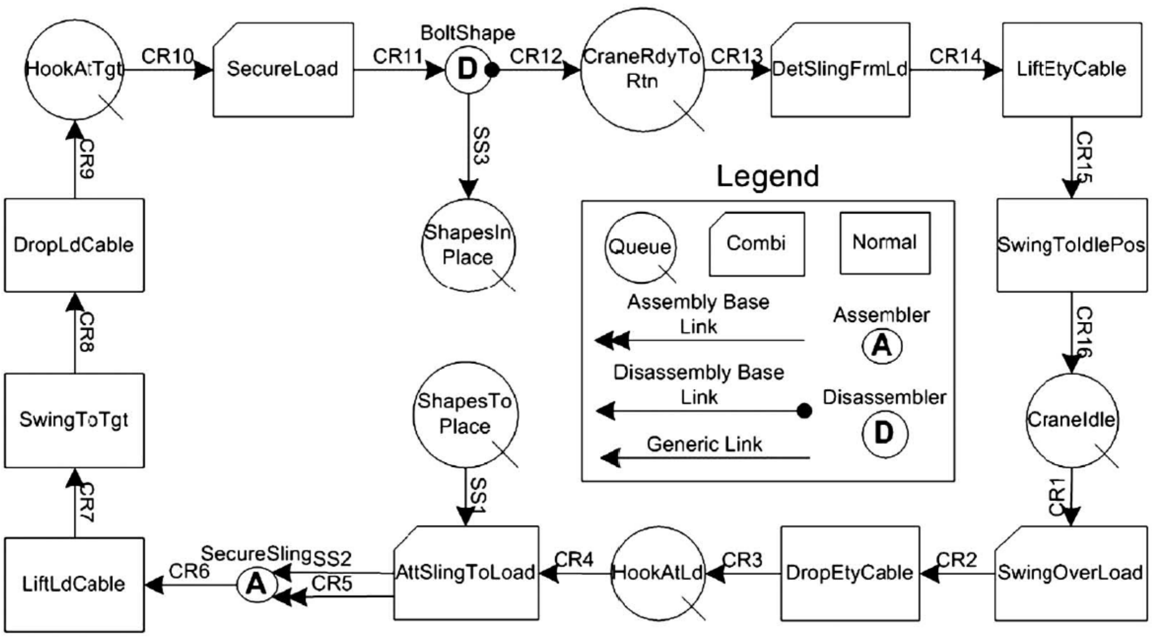


Figure 4. 7: Discrete-Event Simulation Utilizes in the Steel Column Installation

After a comprehensive development and configuration conducted on scene resources in 3DS Max and Unity3D game environment, a major scripting utilizes to dictate the animation produced for each of resources and organize the interaction among them in the virtual world. The scripting uses C# and Java Script (JS) programing language to enable the users to fully control the resources (game objects) interaction during the simulation. The same concept in terms of controllability feature will apply on the Graphical User Interface (GUI) and will be discussed in the next section.

Interactive Visualization

As stated in the research abstract, the core concept is to create an interactive constructability visualization where the users able to interact with the game object smoothly and traverse throughout virtual environment quite similar to their interaction in the real world. In the visualized simulation developed in this research, all game objects involved in the steel column erection process are interactable. To interact with a game object, user (tower crane operator), from one hand, will simply swings the tower crane boom to the suitable position before dropping the hook to pick the column and lift it to the safe height to proceed swinging to the until reaches required position. On the other hand, same user will be able to initiate the workers that are responsible of installing the column in the virtual environment by securely release the column and perform installation process. Figure 4-8 provides a screen shot captures the tower crane movement from begging to the end.

In order to enrich the visualized simulation and make it more informative, more content added to it. This content represented by adding a set of cameras that will allows the user to navigate through the scene and observe the steel column erection process in the virtual environment as he/she would in the real world. Another feature added is the time counting, this feature is particularly beneficial in terms of measuring the learning curve of the user (especially unexperienced one) after iteratively performing this task in the virtual world. Moreover, a productivity display approach conducted to calculate the real world production for the same task been visualized in the virtual world. The calculation utilizes RSmeans (2013 edition) and figure 4-9 shows the breakdown details of this calculation. Figure 4-9 depicts the installation process of the column, task time, cameras, and productivity display

05	Column	Crew	Daily Output	Labor-Hours	Unit	Material	Labor	Equipment	Total	Total Inc O&P
7350	W14 x 74	E-2	984	.057	L.F.	106	2.79	1.55	110.34	122

Floor Height = 10 ft.

Daily Output = 984/10 = 98.4 unit/day

Time in Minute Per Day = 8 hr./day x 60 min/hr. = 480 min/day

Time Needed to Install One Column = 480/98.4 = 4.87 min/unit

Figure 4. 8: Productivity Display Calculation Based on Rsmeans 2013

(1) (2)
(3) (4)
(5) (6)
(7) (8)

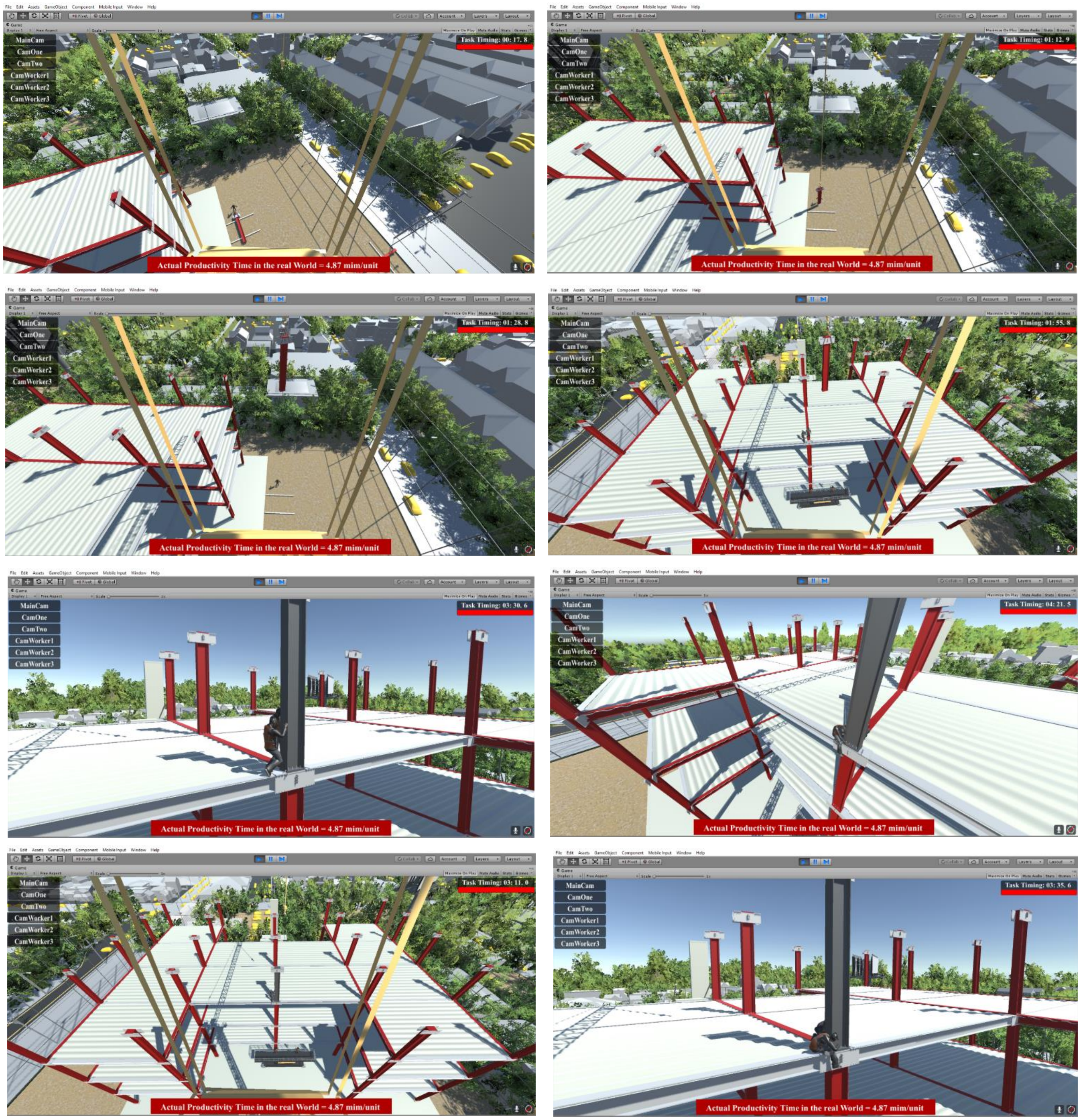


Figure 4. 9: Screen Shots Depicts the Installation Process of the Column, Task Time, Cameras, and Productivity Display

Visualization Assessment

The simulation incorporated construction domain knowledge through various entity components and predefined interaction rules. These rules were parameterized to allow their use in performing similar installation process for the rest of the structure. Only the parameters need to be changed when adopting them in other part of the virtual job site. For instance, the tower carne has separated functionality in terms of the boom control and the operator cabinet control and independently modules to execute lifting functionality and the same concept applied to the workers involves in the installation process. This modular design reduces the otherwise tedious task to create components and rules for each item.

From Figure 4-9 above, we can easily see that the worker on the edge was performing his task difficultly and unsafely. In order to mitigate this issue, a scissor lift was added to the scene to improve safety and productivity to provide more options for decision makers to trade-off between quality and cost of added equipment. Also, more information added to the simulation indicates the installation process and to enhance the communication between users and visualized simulation. Figure 4-10 shows the interactive simulation of this alternative construction method to achieve better project safety and productivity objectives.

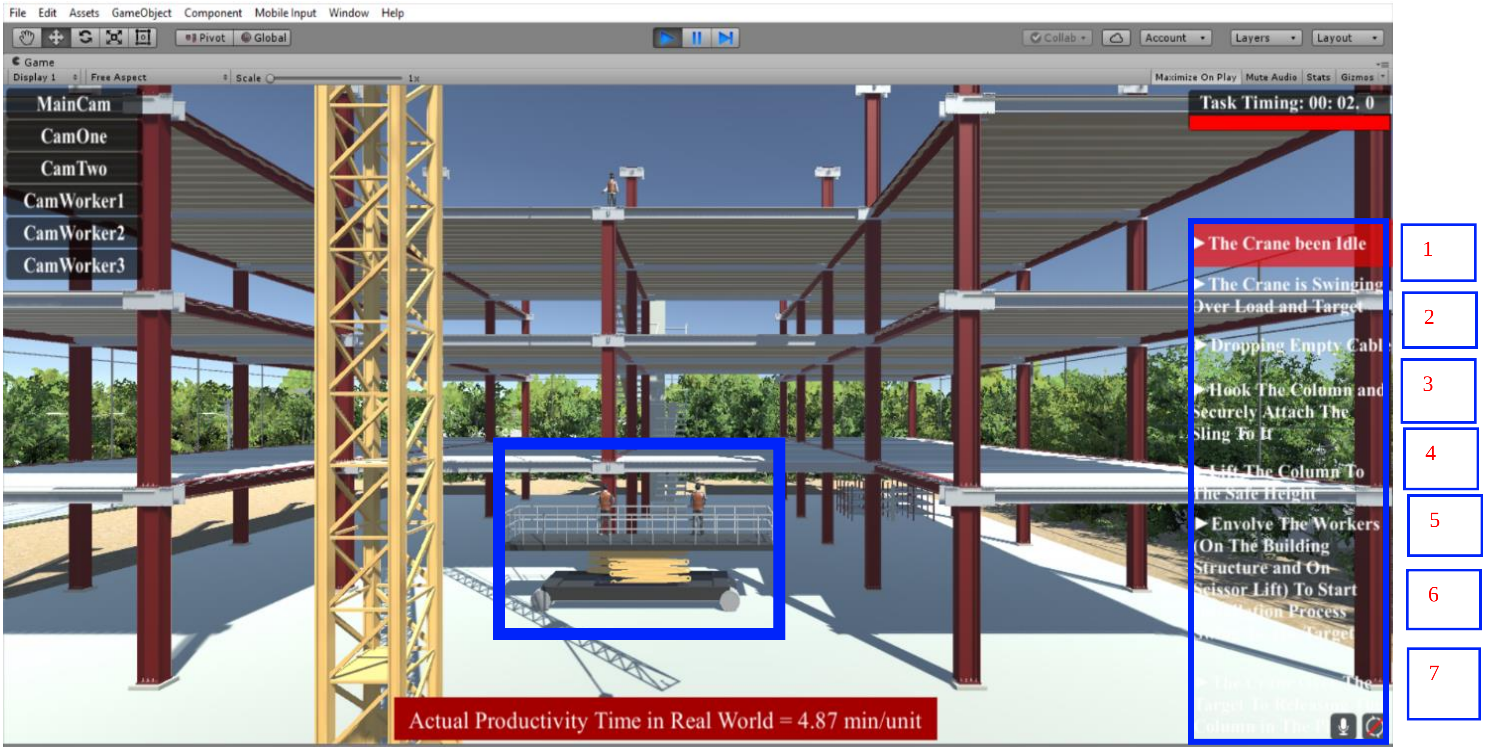
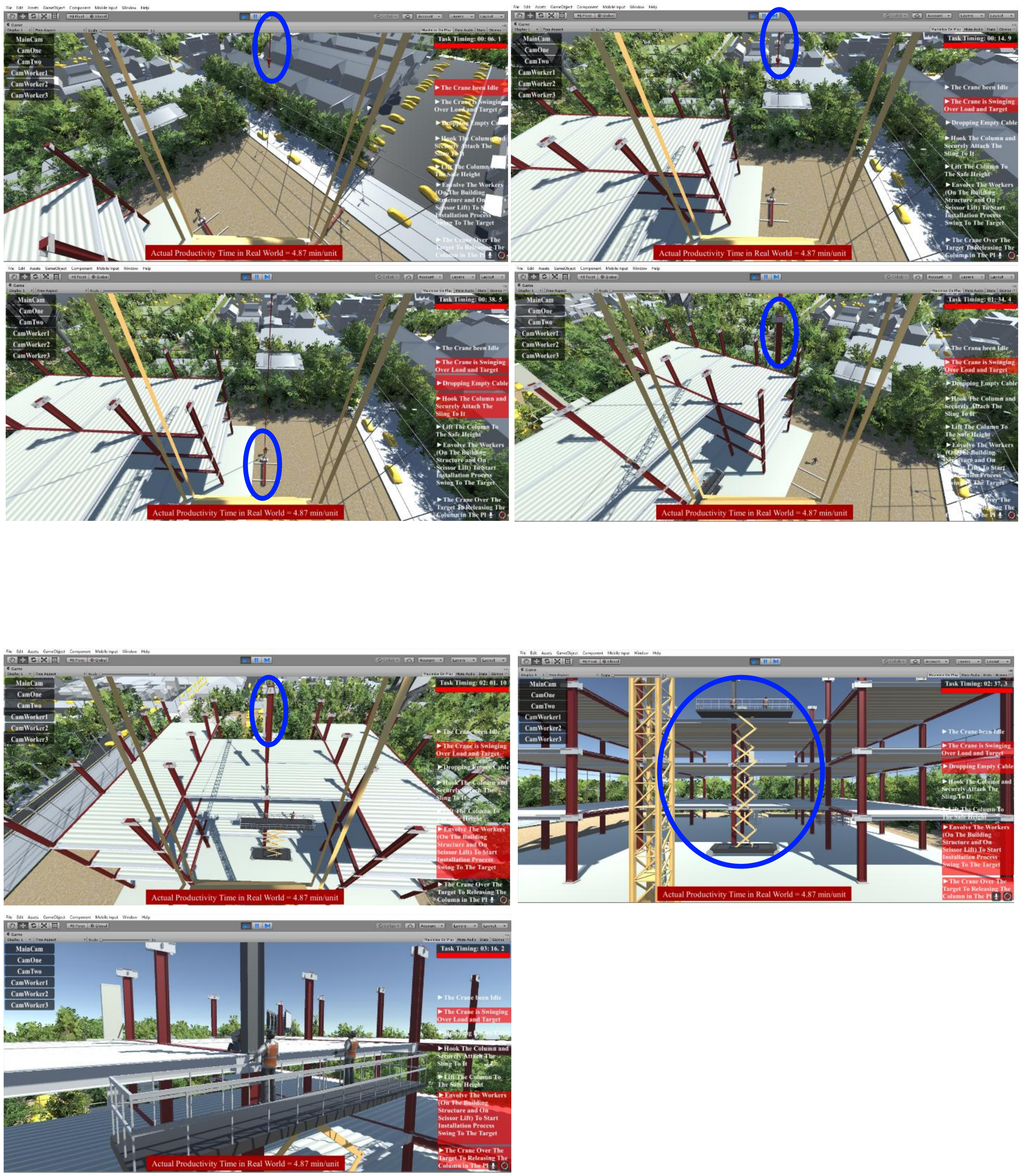


Figure 4. 10: Screen Shot of the Alternative with Scissor Lift Involved in the Installation Process

From observing figure 4-10 above, its shown the scissor lift added and illustrate seven major activities involved in the installation process. Figure 4-11 shows the process in action and these activities as following:

1. Tower crane is being idle.
2. Tower crane is swinging over the load (column)
3. Drop empty cable
4. Attach the column to the empty cable
5. After attachment, lift the column to the safe height
6. Involving the scissor lift equipment in the installation process
7. The crane boom is over the specific targeted position to release the column by workers.



(1) (2) (3) (4) (5) (6) (7)

Figure 4. 11: Shows the Installation Process in Action with Scissor Lift Equipment Added

CHAPTER 5

Conclusion

The constructability visualization has been tremendously conducted as one effective tool to improve constructability analysis throughout providing challenges solutions in a timely manner and enhancing proactive feedback from participants by utilizing technology capabilities. The visualized simulation technique presented in this research facilitates the implementation of effective constructability analysis. This chapter covers concise overview of the research objectives and benefits of utilizing BIM visualization and Unity3D game engine simulation that has been demonstrated in this research.

Research Contribution

This research investigated the value of visualizing and simulating constructability of a steel structure installation, in an interactive and realistic virtual world scene. Unity3D game engine was used to create the simulation and visualization, where the information of the facility came from a BIM model. The case study experiment showed that the simulation and visualization helped identify productivity and safety issues and helped analyzing alternative construction methods to solve such issues. Such a visualization and simulation can be used at the planning and design stages of a project to help with following aspects:

1. Sharing knowledge between stakeholders: sharing construction knowledge and communication among stakeholders during planning and design phases of project lifecycle widely recognized as an efficient approach to alleviate potential challenges that might AEC facing on the jobsite which otherwise can causes notable increase in time and cost. This research illustrates narratively and experimentally the benefits of utilizing BIM and game

simulation as a sophisticated technology to overcome any potential issues related to the constructability implementation as much as possible. These two technologies facilitate the process of knowledge sharing and exchanging information effectively among stakeholders by offering a robust visualization capability and dynamically interactive in the virtual world. Visualized simulation presented in this research equips the stakeholders with an ability to observe and critique any construction operation during the design stage to provide efficient constructability solutions. In addition, such an approach considered as a beneficial way to improve the understanding of the construction teams against other similar issues, so they can implement same future task effectively.

2. Supporting decision makings: within this aspect, a high level of collaboration and communication between stakeholders is highly demanded to produce the optimum design alternative that accommodate the owner requirements. In that scene, BIM visualization and Unity3D game simulation offers a proving virtual interactive environment enables the decision maker to evaluate different design alternatives prior to construction. Reliance on the visualized simulation approach will add a valuable constructability analysis to the final product comparing with traditional design development. Also, conducting visualized simulation incentivize decision makers to generate a solid feasibility study and enhance proactive feedback in a timely manner considering the interdependencies between design and construction. Moreover, the visualization presented in this research open the door to target more complicated construction operations related to complex-shaped buildings taking into account the trend of the temporary buildings now days which makes the constructability analysis implementation a must.

3. Raise workers’ awareness of their operational environment: in same essence, construction workers need to be aware of the environment that they are working in to ensure their safety. The lack of construction knowledge and insufficient training for the workers can poses a challenge towards obtaining cost effective projects and causes schedule delay. The experiment illustrated in this research enabled BIM visualization and Unity3D game simulation as a tools to discuss and visualize different scenario with regard to erecting steel structure column construction operation and workers performing this task. The visualized simulation showed the possibility of how conducting such an approach in the planning and design phases can raise workers awareness, support design for safety, and enhance equipment planning in the jobsite.

Summary

A visualized simulation technique about constructability analysis was presented regarding to erection process of steel structure column as a construction operation chosen for this research. This technique is recognizably different from other traditional 2-dimensional (2D) or even 3-dimensional (3D) dummy constructability analysis models considering the dynamic interactivity feature provided utilizing this technique. Relying on the BIM technology and Unity3D simulation, a high level of collaboration and communication among different project stakeholders can be achieved towards better constructability implementation in early design stages. Also, considering such technique can enhances knowledge sharing and raise awareness of the manpower as well as improve equipment planning in the jobsite within virtual world which enable proactive feedback and reduces design rework in a timely manner.

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