Constructability Assessment Platform Using Customized BIM and 4D Models

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A Thesis in The Department of Building, Civil, and Environmental Engineering

Presented in Partial Fulfillment of the Requirements For the Degree of Master of Applied Science (Building Engineering) at Concordia University Montreal, Quebec, Canada

December 2009

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Abstract

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Implementation of constructability assessment platforms in the construction industry has a potential return on investment concerning time and money. Previous assessment platforms were found to be in complex calculations, dependent on governmental benchmarks, or neglecting time factor impact. In spite of the fact that applying constructability concepts in building designs have led to savings estimated within a range of 1% to 14% of the capital cost, the construction industry still lacks an advanced tool to assess and check for constructability implementations in designs.

The objective of this research is to propose and test a new constructability assessment platform to quantify and check constructability implementations on designs. The proposed methodology upgrades the use of object oriented Building Information Model (BIM) and 4D (3D plus time) simulation model to serve the constructability assessment platform. Factors and sub-factors affecting constructability of building designs have been identified and relatively weighted using the Analytical Hierarchy Process (AHP) and based on a questionnaire survey collected throughout the Canadian provinces. Simple Multi Attribute Rating Technique (SMART) was used to convert subjective input of
experts into utility values based on a new constructability evaluation schemes. The developed assessment model combines the values of AHP and SMART applications to calculate the overall constructability score.

The platform was tested using a case study based on a condominium project located in downtown Montreal based on a proposed user friendly tool. Also the platform was validated by a constructability expert’s feedback. The outcome showed that integrating BIM with 4D simulation models along with AHP and SMART applications can be used as either a guide to alert designers on weak design features or as an aide to facilitate selection of the best constructible design among different alternatives.
I cannot possess the joy associated to this piece without expressing my deepest and most transparent sense of gratitude to those whom helped in achieving this lifelong goal. The guidance from both my faith and my supervisors, Dr. Tarek Zayed and Dr. Sabah Alkass, to which I am deeply indebted to and whose mentorship, provided stimulating suggestions with accompanied encouragement in all prospects and endeavors of this experience.

Furthermore, I cannot forget, to mention the camaraderie and achievements of my colleagues at the Department of Building, Civil & Environmental Engineering whom without their efforts and help, I would still be searching for treasured inklings.

Above all, it is essential that I not forget my commitment to the many blessings of my parents and sisters who empowered the insurmountable support which lead to the fundamentals of my fortitudes in the completion of my graduate degree.
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I.1 Research Background

Construction is a dynamic, complex, as well as fragmented process, and the traditional system of construction separates the two main disciplines of design and construction, where designers and contractors rarely communicate before the initiation of the construction phase. These characteristics have produced a decrease in quality and cost efficiency of projects, due to lack of integration of construction knowledge into design (Uhlik et al., 1998). National Institute of Standards and Technology (NIST) conducted a study in 2004 and reported that the lack of an Architecture/Engineering/Construction (AEC) interoperable software is costing the industry $15.8 Billion annually (Gallaher, 2004). Moreover, a study made by the US Bureau of Labor Statistics - shows that construction has had a decreasing rate in productivity since 1964, while all other industries have had an increase in productivity by over 200% during the same period (AIA, 2007). The Business Roundtable analyzed these issues two decades ago and defined a “constructability program” where a potential return on investment of 10:1 is reported by applying constructability (Business Roundtable, 1982). The commonly quoted definition of constructability by the Construction Industry Research and Information Association (CIRIA) is “the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building “(CIRIA, 1983). Another most commonly quoted notion is “the optimum integration of construction knowledge and experience in planning, engineering,
procurement, and field operations to achieve overall project objectives" (CII, 1986). This signifies the fact that building design has a critical impact on constructability.

Constructability of designs have complex relationships with time, cost, and quality performance, which are often ignored by building clients until construction starts, causing surprises and concerns (Lam et al., 2007). Hence, by translating the abstract concept of constructability into something physical and recognizable to project stakeholders, improvement and assessment of constructability of designs can be applicable. Constructability should be an important objective throughout all phases of project construction (Eldin, 1999). Designers play an important role in achieving superior constructability and their decisions should include constructability input and critiques in order to serve as guide lines or road maps for advanced constructible projects. From this perspective, constructability is encouraged to be applied during the design phase as to achieve maximum benefits (Fischer and Tatum, 1997).

Constructability, because of its abstract nature, requires implicit understandings before improvements can be realized. One of three main approaches to improve and enhance constructability is through quantified assessment of designs. Quantifying assessments enables an objective evaluation of constructability attributes while results can be comparable. On the other hand, it is difficult to comprehensively take into account of all relevant factors affecting constructability into the assessment system (Wong et al., 2007).
With the continuous advancement in technologies, new techniques are constantly being developed in order to improve engineering implementations for the construction industry. One of these promising developments is Building Information Modeling (BIM) where it facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration (Eastman et al., 2008). The American Society of Civil Engineer (ASCE) reported that BIM technology can be used to validate a new constructible tool (Gambatese et al., 2007).

1.2 RESEARCH MOTIVATION

Constructability can help improving the profit margin of a construction project, practitioners can use it as a means to reduce waste and increase productivity (Fox et al., 2002). The most significant benefits of constructability implementations recorded reduction of claims, costs and time of projects as well as an increase in quality and faster construction process (Arditi et al., 2002). The importance of research to study constructability is based on these benefits. Researchers have also shown that Building Information Model (BIM) is emerging as a tool that helps project teams’ work together to increase productivity and improve outcomes for all stakeholders. This is driving the most “transformative evolution the construction industry has ever experienced” (Eastman et al., 2008). The ACSE has reported that “the potential of new technology-based tools such as four-dimensional CAD or building information modeling (BIM) have not been fully realized. This area could also include validation of new constructability software” (Gambatese et al., 2007). Thus, the A/E/C industry will
definitely benefit from new tools and implementations in the area of improving constructability of projects by using advanced technologies such as BIM and 4D model.

I.3 PROBLEM STATEMENT

Hei developed and implemented an empirical system for scoring constructability of designs in the Hong Kong construction industry (Hei, 2007). The Singaporean Government introduced the Buildable Design Appraisal System (BDAS) in 2001 where a mathematical model was developed based on standardization, simplicity and single integrated elements (BCA, 2005). Another Buildable Multi-Attribute System (BMAS) was proposed for the Malaysian Government where a five-point scale (very low to very high) was established to evaluate each building component (Zin et al., 2004). A cognitive model for constructability assessment based on knowledge mining and protocol analysis was established by (Ugwa et al., 2004). A fuzzy quality function deployment system for constructability design decision was elaborated by (Yang et al., 2003) to model constructability implementation on a given design. Main limitations to the preceding researches were documented. Mathematical models needs trustworthy benchmarks to evaluate the assessed score, these benchmarks are time-consuming; rely on governmental statistics, not generic and need continuous updates (Wong et al., 2007). Time factor was not presented in any of the previous works, thus analyzing the sequence of installed components and resource associability cannot be done. Fuzzy models are demanding assessment models were the user must assign many attributes: weight factors, client satisfaction indices, constructability aspects values, etc… (Hei, 2007).
In summary, the problem statement can be defined as the lack of a clear advanced approach to quantify the impact of constructability implementation on designs. The platform must be independent of benchmarks, complex calculations and relies primarily on design components. Figure I-1 summarizes this approach.

Figure I-1: Problem Statement Approach
1.4 Research Objectives

The main objective of the current research is to propose and test a constructability assessment platform for designers to evaluate the level of constructability principles’ implementation on building projects. The platform constitutes of a set of tools and techniques integrated for a single output which will assist designers in revising constructability issues and thus improving their designs.

The sub objectives that complement the main goal are:

- Identify, study and weight design constructability factors,
- Study and extend the use of BIM models to collect constructability inputs,
- Develop a 4D model to study the effect of time factors on building designs,
- Develop a data model to categorize and automate the integration process between constructability information and building construction data,
- Develop an evaluation scheme to rate the impact of constructability implementation on design,
- Generate a constructability assessment model,
- Develop a user friendly tool to run the proposed constructability assessment platform.

1.5 Research Methodology

The research methodology consists of several stages. 1- An extensive literature review of constructability factors that affect project designs during the pre-construction phase. 2- Data collection through a questionnaire survey to assess the relative weights of these factors. 3- A BIM and a 4D model will be developed and linked to the pre-defined
design factors and attributes using Microsoft Access© database. 4- The assessment model will be based on the calculations of two techniques (Analytical Hierarchy Process) AHP and Simple Multi-Attribute Rating Technique (SMART) so that constructability impacts on designs can be utilized as quantified values. 5- A case study will be used to test and validate the developed platform. An Access©-based application will be built to allow the proposed framework to be used by different stakeholders. The following sections explain briefly the main steps followed for the proposed methodology.

I.5.1 LITERATURE REVIEW

All topics related to constructability concepts and constructability assessments are reviewed in order to have a better overview of the topic and to understand how to solve the proposed problem. Topics studies in this section are: constructability implementations and improvements, building information modeling concepts, multi criteria decision making and analysis of previous work related to constructability assessment.

I.5.2 DATA COLLECTION

The data collection process consists of four stages. In stage one; the data on constructability is collected from various literature sources and experts via a questionnaire survey. The data collected, forms the fundamentals to weight the various selected constructability factors that has to be incorporated in the framework. In stage two; criteria rationale is identified to establish evaluations schemes which are essential to the SMART application and thus assists the individual in their evaluations. Stage three, explains how constructability data will be collected from BIM and 4D models to be used
in the assessment model. The last stage discusses the information needed to implement the case study.

1.5.3 BIM AND 4D MODEL

A BIM model is developed to generate the design by integrating building construction data with design components. This model will generate and constructability data of the building as the project team process designs. Also, each building component will be linked to its corresponding time factor to form a 4D model. The 4D model will be used to evaluate the sequence of building construction, check the effect of proposed time schedule on constructability and analyze resources accessibility.

1.5.4 CONSTRUCTABILITY ASSESSMENT MODEL

The assessment model are developed based on two techniques (Analytical Hierarchy Process) AHP and Simple Multi-Attribute Rating Technique (SMART). AHP will be used to weight pre-defined factors and SMART will be used to rate the impact of constructability on design. BIM and 4D model will offer the virtual medium which will be used as data input repository for SMART applications.

1.6 THESIS ORGANIZATION

As previously stated, the main objective of this research is to propose a constructability assessment platform and implement it using advanced technologies. Accordingly, the thesis is organized to achieve this objective.
The literature review is compiled and organized in Chapter II, including constructability concept, measures for improving constructability, building information modeling, integrated project delivery approach and multi criteria decision making. Previous work related to constructability assessment is also reviewed and application limitations are recorded.

Chapter III gives an overview of the research methodology followed in this research. Moreover, it includes an overview of the developed model along with the implementation strategy to run the platform.

Chapter IV describes the data collection process. Data is needed in order to perform two main tasks: to build the model and to identify evaluation schemes that guide the rating process.

Chapter V explains in detail the development and the implementation of the constructability assessment framework. It introduces the developed process to generate BIM and 4D simulations, the rationale used to build the data model and building the assessment model. Furthermore, a new implementation strategy is proposed along with a user friendly application. As a proof of concept, a case study is demonstrated, processed and analyzed using the proposed developed tool.

Chapter VI presents the conclusions and recommendations. It includes the limitations of the developed model and application, research contributions, research enhancement and extension of the research in the future.

References and appendices are found in Chapter VII.
In the last two decades, the construction industry experienced the lack of constructability implementation. This caused many problems, such as rework, increased cost and time required for constructing a project, reduced productivity of project personnel and equipment, and low quality construction (Nima et al., 1999). In order to approach and improve constructability implementation, literature review on many topics is conducted and presented in this chapter. Figure II.1 illustrates the different literature topics reviewed in the following sections.

Figure II-1: Literature Review Chapter Layout
II.1 CONSTRUCTABILITY CONCEPTS

II.1.1 CONSTRUCTABILITY BACKGROUND

In historic times, design was characterized by how the project was going to be built while the design and construction activities were done together by the "master builder". Typically, construction was based on traditions, common rules, and trial and error techniques. This situation continued until the Renaissance, when the architectural profession emerged. During this period, some architects valued the visual over the physical aspects of the buildings. This was the time when design began to separate from building or construction (Uhlik, 1998).

This long-standing problem was first officially recognized by Emmerson (1962). While researchers and academics tried to integrate design and construction stages throughout dissimilar expertise and disciplines, contractors encountered difficulties while working on site. Construction problems increased with designers of shallow construction knowledge or experience and especially with who disregard the importance of constructability as an important design consideration. These unsolved problems are left to contractors who are supposed to plan the construction process to meet design requirements (Griffith and Sidwell, 1997). As a direct response to this increasing challenge, the Business Roundtable defined “constructability programs” as a first step to solve this dispute. The benefits to be gained from good constructability were identified as "approximately 10 to 20 times the cost of achieving it" by the Business Roundtable two decades ago (Business Roundtable, 1982). The Construction Industry Institute (CII) also published guiding principles for implementing constructability in the form of constructability concepts.
covering 14 defined construction milestones, i.e. 6 for the conceptual planning phase, 7 for the design and procurement phases and 1 for the field operations phase (CII, 1986). Following up with the increase of building complexity and the advances in construction methods and techniques, constructability concepts are being modified continuously in order to meet new challenges when applied in dissimilar construction industries.

II.1.2 INTERPRETATIONS OF CONSTRUCTABILITY AND BUILDABILITY

In the United States (US), the term of "constructability", is used rather than "Buildability". With respect to "constructability", the most commonly quoted notion is "the optimum integration of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives" (CII, 1986). As for "Buildability", the most publicized notion is the one developed by the Construction Industry Research and Information Association (CIRIA) as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building" (CIRIA, 1983). Constructability has also been given a diverse range of interpretations, related to integration of construction knowledge and experience.

The definition of constructability as represented in the literature is illustrated in the following sections. Constructability is defined as a measure of the ease or expediency with which a facility can be constructed (Hugo et al., 1990). Others state, that it is rather considered as the application of a disciplined and systematic optimization of construction-related knowledge during the planning, design, procurement and construction stages by knowledgeable, experienced construction personnel who, in turn,
were part of a project team (CMC, 1991). Kerridge believes that constructability is the process of doing everything possible to make construction easy, to improve quality, safety, and productivity, to shorten construction schedules and to reduce rejection and rework (Kerridge, 1993). Constructability involved construction-oriented input into the planning, design and field operations of a construction project (Pepper, 1994). Constructability programs were defined as the application of a disciplined, systematic optimization of the procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team (Russell et al., 1994). Constructability was often portrayed as integrating construction knowledge, resources, technology, and experience into the engineering and design of a project (Anderson et al., 1995). Constructability of a design referred to the ease with which the raw materials of the construction process (labor, production equipment and tools, and materials and installed equipment) can be brought together by a builder to complete the project in a timely and economic manner (Glavinich, 1995). The integration of construction knowledge in the project delivery process and balancing the various project and environmental constraints to achieve the project goals and building performance at an optimum level is another definition by (CII Australia, 1996). Geiles states that constructability is "a planning process that required customer input in every phase of the capital project planning: front-end engineering; detailed design, procurement, contracting, construction, check-out, start-up, operation, maintenance, and business management, and communication among all project participants." (Geile, 1996). Constructability as the optimum use of construction knowledge and experience by the owner, engineer, contractor and construction manager in the conceptual planning,
detailed engineering, procurement and field operations phases to achieve the overall project objectives is proposed by (Nima et al., 1999). (Yu and Skibniewski, 1999) Believes that it is the feasibility (or complexity) of a considered project to be performed by a specific technology based on the construction knowledge learned from past projects. Constructability programs aimed at integrating engineering, construction, and operation knowledge and experience to better achieve project objectives (Arditi et al., 2002)

In summary, below is the list of commonalities of the perceptual attributes of constructability; which are based on the previous stated definitions; that will be used for the purpose of this thesis:

- Integration of construction knowledge and experience
- Involvement of various project stakeholders
- Achievement of project goal and objectives
- Easiness of construction

II.1.3 Knowledge Management During Constructability Process

By identifying the brief attributes of design, the abstract concept of constructability can be expressed in a more defined and concrete way and thus making its improvement easier. Management of knowledge and information of constructability process is a complex subject. In this regards four areas in this domain were identified and reviewed: knowledge classification, knowledge acquisition, knowledge representation and computerized systems for Knowledge Management (KM) (Yang et al., 2003).
Several results has been reported in the literature of constructability knowledge acquisition domain including: a classification system for construction technology (Tatum, 1988), constructability knowledge platform for input to the design process using expert system techniques (Fischer and Tatum, 1997), and constructability knowledge in the IF/THEN format (Skibniewski et al., 1997). Construction and design relevant attributes are mainly derived from the works of Hanlon and Sanvido (1995), Fisher and Tatum (1997) and Richard (1986). More sub attributes can be added to the presented list to meet specific needs for the designers. Figure II-2 shows categories and attributes of information for constructability concepts by Hanlon and Sanvido, while Figure II-3 shows categories and subcategories for constructability knowledge management by Richard; Fisher and Tatum.

![Constructability Concept Diagram]

Figure II-2 : Constructability Categories and Attributes (Hanlon and Sanvido, 1995)
II.1.4 Stages of Implementations of Constructability Analysis

Failure of a designer to consider how the design will be constructed by a contractor can result in scheduling problems and delays during the construction process. The integration of construction knowledge and experience into the early design phase provides the best opportunity to improve overall project performance in the construction industry (CII, 1986; Hanlon and Sanvido, 1995; Fischer and Tatum, 1997). An overwhelming majority of researchers proposed measures to be taken at the design stage as the best time to apply constructability (Pepper, 1994; Anderson et al., 1995; Glavinich, 1995; Gibson et al., 1996; Low, 2001; Arditi et al., 2002; Fox et al., 2002).
Some suggested improvement measures should be carried-out throughout the whole building process (Geile, 1996; Griffith and Sidwell, 1997). Whilst others applied their measures only at various stages of briefing, conceptual planning, design, procurement, construction, contract review and tendering, etc. (Uhlik and Lores, 1998; Anderson et al., 2000; Jergeas and Put, 2001; Low and Abeyegoonasekera, 2001; Nima et al., 1999).

Constructability, when introduced into the design process, provides the information necessary to achieve the early definition of the whole building scope. Thus, an early integration of construction knowledge during the conceptual design phase allows for better coordination with building materials, reliable estimates of cost, refined schedules, and the development of necessary sections and details (Glavinich, 1995). Based on this explanation, this research will study constructability during the design phase only.

**II.1.5 Importance and Benefits of Constructability**

Initially, the benefits of improved constructability are usually noticed in terms of cost and time saving. Learning from isolated examples of incorporating construction knowledge into the design, led to savings estimated within a range of 1% to 14% of the capital cost (Gray, 1983). Other studies recorded 10.2% savings in project time and 7.2% in project cost (Russell et al., 1992-a). Further studies have substantiated the improvements resulting in savings of total project cost (Alkass et al., 1992, Pepper, 1994; Geile, 1996; Griffith and Sidwell, 1997; Eldin, 1999; Francis et al., 1999; Jergeas and Put, 2001). In particular, lower cost of bidding (Gibson et al., 1996), reduced site labor
(Lam et al., 2006), increased cost effectiveness (Low and Abeyegoonasekera, 2001), and better resource utilization (Eldin, 1999) have been reported. It is also reasonable to suppose that the building process can be more efficient and economical, which eventually results in cost saving, due to the incorporation of construction expertise and experience at the design stage (Ugwa et al., 2004). Building projects, for which constructability is consciously performed, will ultimately undergo smooth construction, thereby enhancing quality of the built products and minimizing potential disputes and avoiding accidents on site (Yang et al., 2003; Zin et al., 2004). As more studies were carried out, more benefits have been identified in terms of time, quality and safety as well as intangible bonuses. Figure II-4 sheds light on this aspect. Benefits in relation to time were referred to as early-completion (Griffith and Sidwell, 1997; Eldin, 1999; Francis et al., 1999; Low and Abeyegoonasekera, 2001) and increased productivity (Poh and Chen, 1998; Low, 2001). Higher quality of the built products was also achieved (Eldin, 1999; Francis et al., 1999; Low, 2001; Low and Abeyegoonasekera, 2001). Regarding safety aspect, a safer environment on-site and better safety performance would result (Francis et al., 1999; Low and Abeyegoonasekera, 2001). Apart from the above, intangible bonuses were noticeable, such as a reduction in unforeseen problems, improvements in industrial relations, team work, communication as well as enhancement of client's satisfaction (Francis et al., 1999), alongside with the creation of good working relationships among stakeholders (Geile, 1996; Eldin, 1999). It is obvious that as a direct result of constructability improvement, construction becomes easier and project periods can be shortened (Poh and Chen, 1998).
The main direct benefits of constructability are:

- Construction planning is easier
- Design and construction costs can be reduced
- Construction schedule may be shortened
- Better quality can be achieved

On the other hand the indirect benefits are:

- Earlier owner occupation
- Building a collaborative team committed to project goals
- Cross discipline training
- Transfer of expertise from other projects
- Constructors better understand design intent,
• Increased innovation in both design and construction processes
• Competitive advantage among different constructability firms

II.1.6 Barriers of Constructability Implementation

The construction industry has unconsciously and unknowingly created barriers against changes which would lead to improvement of constructability. A barrier to constructability is any significant feature that prevents effective implementation of a constructability program (O’Connor and Miller, 1994). For instance, design professionals find it difficult to appreciate the abstract concept of constructability, especially when they lack adequate knowledge and experience in construction operations. Added to this, where the traditional design-bid-build procurement method and construction systems still dominate in the industry, clients and designers are reluctant to disclose much information to contractors before the contracts are awarded (Ma et al., 2001). A brief list of possible or potential barriers to constructability is presented here and it was compiled by the following researchers (O’Connor and Miller, 1994; Griffith and Sidwell, 1997; Uhlik and Lores, 1998; Ma et al., 2001). The first list will concentrate mainly on barriers from designers’ point of view:

• Perception that "we do it"
• Lack of awareness of constructability benefits, concepts, etc.
• Lack of construction experience
• Company goals over project goals
• Lack of awareness of construction technologies
• Lack of mutual respect between designers and constructors
• Perception of increased designer liability
• Construction input is requested too late to be of value

As for the barriers’ from the contractors’ side:

• Reluctance of field personnel to offer preconstruction advice
• Poor timeliness of input
• Poor communication skills
• Lack of involvement in tools and equipments development

**II.1.7 BIM and Constructability**

The abstract concept of constructability knowledge can be easily understood when its inputs are well identified and organized (Fischer and Tatum, 1997). Integrating data output from Building Information Modeling (BIM) components and linking them to their respective constructability principles, will help organize the complex data from any given design proposal. Building components attributes found in an object oriented model can be modified as to accept new attributes related to constructability (Eastman et al., 2008). Based on the above, the integration of the constructability concepts with their corresponding building components can facilitate constructability building analysis.

**II.2 Measures for Improving Constructability**

As described in section II.1.5, the benefits of improved constructability have long been associated with the time, cost, quality and safety performance of a project, together with other intangible benefits. By reviewing current literature published in academic journals and construction magazines, it was found that quantifying assessment of designs;
constructability review; and implementation of constructability programmers, is the 3 most commonly employed approaches. These three approaches are discussed in details in the following section.

II.2.1 QUANTIFIED ASSESSMENT OF DESIGN

Quantifying assessment of designs enables an objective evaluation of constructability attributes since results are comparable. Using this approach, two issues were recorded. On one hand, it is reasonably practicable and manageable for assessments to be made because it is done using the finished design product rather than evaluating the design process. On the other hand, it is difficult to comprehensively take into account all relevant factors affecting constructability into the assessment system (Wong et al., 2007). Aspects that are taken into consideration for assessment purposes are usually based on the project managers’ goals and objectives concerning a specified project. The approach of quantifying assessment is formally adopted through the Buildable Design Appraisal System (BDAS) in Singapore. This approach requires minimum constructability performance as a prerequisite for building plan approval (BCA, 2005; Poh and Chen, 1998; Low, 2001; Lam, 2002). Others adopted the Fuzzy Quality Function Deployment system (Yang et al., 2003), the knowledge models for automated constructability assessment (Ugwu et al., 2004), and the assessment framework of constructability in Malaysia (Zin et al., 2004).

II.2.2 CONSTRUCTABILITY REVIEW

This approach refers to evaluating design documents at an early construction stage to ensure smooth project delivery. It helps to guard against any discrepancies or
errors and ensure coordination of design documents including drawings and specifications (Wong et al., 2007). This kind of review increases the possibility to oversee problems that may arise during construction, prior to initiation of actual site works. Nevertheless, carrying out constructability review needs additional time and resources, not to mention the need to overcome potential resistance from design consultants, who may regard contractors as the party primarily responsible for constructability (Ford et al., 2004). Constructability reviews were implemented by researches using different methodologies and stages of implementations: early implementation of the review in the conceptual planning stage (Arditi et al., 2002), integration of constructability improvements into project development (Anderson et al., 2000), integration of analytical review tools into the constructability review process (Fisher et al., 2000), implementation of the constructability review process at different project stages (Young, 1998), the in-house design-phase constructability review (Glavinich, 1995), and the carrying out of constructability review by an independent team with hands-on experience in similar projects (Pepper, 1994).

II.2.3 IMPLEMENTATION OF CONSTRUCTABILITY PROGRAMS

This is based on the use of constructability programs which consists of a set of rules and guidelines linked to the management process. This measure embodies all factors affecting constructability and involves interaction with different project stakeholders at various project stages (Uhlik and Lores, 1998). Monitoring the whole process of constructability programs is not practical, whereas snap-shots observed during parts of the process may not be well representative (Wong et al., 2007). Various researches
discussed this approach by implementing constructability programs at various project stages (Opfer, 1994; Anderson et al., 1995; Geile, 1996; Uhlik and Lores, 1998; Jergeas and Put, 2001).

II.3 BUILDING INFORMATION MODELING (BIM)

Building Information Modeling (BIM) is defined as the creation and use of coordinated, consistent, computable information about a building project. These various forms of information have a parametric nature where they can be used for design decision making, production of high-quality construction documents, prediction of building performance, cost estimating, and construction planning (Krygiel et al., 2008). With the introduction of BIM, constructability has become much more critical. BIM is not just a combination of design technologies that represent every building component in a virtual environment, nor is it merely a 3D rendering of a building. Rather, BIM is a radical departure from the traditional design delivery process to a more integrated process (Eastman et al., 2008). BIM provides the construction community a complete 3D database that can be downloaded for estimating, scheduling, detailing, advance bill production, automated shop drawing, and construction planning for all of the trades. In short, BIM is a means to communicate a complete project delivery concept developed with constructability based design philosophy (Edgar, 2007).

II.3.1 WHY BIM

Over the past 100 years, the building industry has changed dramatically. Buildings have become much more complex with many interconnected and integrated
systems. This complexity has forced the designers in the A/E/C industry to consider more inputs in their design analysis (John et al., 2005). With the added complications, architects, owners, and contractors had to adapt to these changes and take in considerations more factors than before in order to keep up with the continuously growing industry. To analyze these factors in a proper manner where all communication requirements are met, designers are searching for better ways to coordinate all this information together throughout all the parties' involved (Krygiel et al., 2008). BIM can be used as a platform for this purpose.

BIM plays a crucial role in research and development fields of construction information integration and interoperability. Now, it is feasible to have one repository that stores all design components' data while each component is described only once. Both graphical and non-graphical documents, such as drawings, specifications, schedules, etc., are included. Changes to each item are made in only one place and for once so that all project participants can monitor the same modified information instantly. Hence, by handling project documentation in this means, communication problems that retard projects and increase costs can be greatly reduced (Cyon Research, 2003). A basic principle of BIM is the possibility for different stakeholders at different phases of the life cycle of a facility to insert, extract, update or modify information in the building model. In conclusion, BIM is a shared digital representation founded on open standards for interoperability (Edgar, 2007).
II.3.2 BIM DESCRIPTIONS, CAPABILITIES AND BENEFITS

The goal of adopting a BIM methodology is to allow an overall view of the building or project by including everything (drawings, specification, details, etc...) in a single-source model (Krygiel et al., 2008). Graphisoft’s description for BIM is “a standard digital / computer model information repository of building design, which may also contain information about the building’s construction, management, operations and maintenance (Graphisoft, 2003). An integrated BIM model should include the information of construction and maintenance activities linked to the relevant building physical components. These activities should also be described by the phases of building construction and management (Fu et al., 2006). BIM databases contain physical and functional characteristics of a structure since a BIM model is composed of intelligent objects rather than lines, arcs, and text (McGraw, 2008). All of these characteristics are primarily due to BIM’s ability to virtually realize the building through all of the stages of the design process in the form of a database. The basic benefits of a BIM-based model are:

i. 3D SIMULATION VS. 2D REPRESENTATION

A two dimensional (2D) drawing is merely a representation of the final design which forms abstract plans, section, and elevations. BIM allows a three dimension (3D) simulation of the building and its components. This simulation goes beyond demonstrating how different building assemblies can be combined in the project. It can predict collisions, show construction variables on different building designs, and calculate material quantities and time periods (Eastman et al., 2008).
ii. **Accuracy vs. Estimation**

By having the possibility to build the whole project virtually before physical construction begins, BIM adds a level of accuracy to both quantities and quality issues that overcomes the shortfalls found when traditional processes of design and documentation are used. Building materials as well as environmental aspects can be demonstrated in real-time scenarios rather than manual analysis (Krygiel et al., 2008).

iii. **Efficiency vs. Redundancy**

By drawing building elements only once for the project in a plan view, the projections of all elevations and sections are generated automatically in short period of time. One of the direct benefits that can be recorded is the reduction of drawing time and thus designers can primarily focus on other design issues (Krygiel et al., 2008).

To conclude this section, the main benefits to virtually design new or modify existing facilities using BIM technology are (Eastman et al., 2008, Edgar, 2007):

- to coordinate design documentation,
- to simulate construction process and operation activities prior to physical implementation,
- to drive out problems and predict performance,
- to coordinate the construction to reduce construction time and eliminate change orders
- To facilitate data entry as part of the construction business process and then reuses it throughout the whole project lifecycle and beyond.
II.3.3 BIM TOOLS AND PARAMETRIC MODELING

In comparison to earlier Computer Aided Design (CAD) systems, BIM-based CAD systems are object-oriented systems, in which the basic components of drawings are building elements like walls, doors, windows and so on, rather than geometric elements as in earlier CAD systems, such as dots, lines and polygons (Fu et al., 2006). Traditional 2D and 3D CAD programs don't represent a space because it doesn't exist as a distinct physical entity. However, a space entity will be a fundamental part of a BIM model, and will include the proper relationships to its corresponding walls; ceilings, floors, etc. Thus, spaces' information that will be needed for constructability analysis can be easily obtained from an application using a BIM data model as shown in Figure II-5, whereas several complex calculations had to be required to derive the same information from an application using a traditional geometric data model (Khemlani, 2004).

![Diagram](image)

**Figure II-5: Geometric Model vs. Data Model (Khemlani, 2004)**
As the use of BIM models starts to gain momentum, new tools and technique are being implemented into the design and construction process. Some of these achievements are:

1. **Integrated Documents:** Since all drawings in a BIM model are stored within a single integrated model, document coordination becomes relatively automatic. Being able to automatically coordinate the complex process of integrating all building systems’ information can generate benefits to all parties and reduces time consumption. For example integrating consultant information into the architectural drawings can facilitate communications and improves design quality. Since the building is modeled in a 3D environment, designers can easily overlay architectural, structural, and mechanical models and check for interferences and conflicts within the building (Eastman et al., 2008).

2. **Design visualization:** The 3D capabilities provided by BIM, are not only used to convert ideas from the architect to other stakeholders, but rather to additionally demonstrate different design analysis methods such as sun effect, shade effect, energy modeling, etc… (Krygiel et al., 2008).

3. **Material databases:** Since BIM creates a database of the virtual building; assemblies that are modeled can be created with their physical properties. When the architect draws a wall, he or she is not drawing 2 parallel lines as in traditional 2D drafting, but they are creating an object that constitute the raw materials which this particular wall is made up off. This aspect will assist the BIM software to create detailed material schedules and quantities based on a single building model. Moreover, since all the data is automatically linked together, any single
modification to any BIM object will update the whole material databases (Krygiel et
al., 2008).

4. Construction planning: Demonstrating building visualization to builders can also
save time on the job site. A contractor who is familiar with BIM can use it to
identify areas of a project that traditional documents do not permit him or her to
visualize quickly. These areas can also be rapidly captured and returned to the
design team to request further elaboration on that portion of the project. BIM can be
useful by breaking down the model into separate phases within regular time
intervals to show construction staging (McGraw, 2008, Fu et al., 2006).

5. Export model geometry: Designers can manage and reuse the building geometry
from a BIM model by exporting it into different analysis packages as to study
various aspects concerning energy, solar, day lighting and so on. By simply re-
creating building geometry in another application more assessments and
investigations can be done on the proposed building as to improve its overall

II.3.4 VALUE OF BIM TO THE CONSTRUCTION INDUSTRY

McGraw Hill Construction issued a report entitled “Building Information Modeling
(BIM): Transforming design and Construction to Achieve Greater Industry Productivity“
on December 2008 (McGraw, 2008), presenting the impact of using BIM in the
construction industry in the US. This report, which is produced in collaboration with 23
construction industry organizations ;including 15 associations and the U.S. Army Corps
of Engineers ; is based on extensive interviews with hundreds of owners, architects, civil,
structural, and MEP engineers, construction managers, general contractors and trade
contractors who are currently using BIM (McGraw, 2008). The key findings are listed here and presented in Figure II-6:

- 62% of BIM users will use BIM in more than 30% of their projects in 2009.
- 82% of BIM experts believe that BIM has a very positive impact on their company’s productivity.
- 72% of BIM users say that BIM has had an impact on their internal project processes.

Measuring the value of BIM indicates that 48% of respondents are tracking BIM return on investment (ROI) at a moderate level or above. Results from companies who are actively tracking BIM return on investment (ROI) are showing initial BIM ROIs of 300 to 500% on projects where BIM was used (McGraw, 2008).

![Pie charts showing distribution of BIM users by percentage of projects in 2008 and projected distribution in 2009.]

Figure II-6: Growth in BIM Use on Projects (McGraw, 2008)

Another report issued by Bentley recorded the results of a survey conducted in 2007 to evaluate the use of BIM solutions. While architecture was the predominant discipline that was represented, there were also a sizable proportion of respondents practicing from engineering, construction, and facilities management and operations backgrounds. The
number of respondents from large, multi-firm offices was almost the same as those from smaller, single-office firms. Key results of the survey are (Bentley, 2007):

- 20% project cost savings
- 25% faster delivery
- 35% improved safety record
- 30% increased productivity
- Much improved quality
- Competitive Advantage

II.3.5 Fourth Dimension (4D) Simulation Tool

Fourth dimension (4D) models are 3D model plus time factor. 4D models utilize a 3 dimensional project geometry into an environment where the effect of time schedule over construction can be visualized. The timeline can be in all stages of the project: pre-construction, construction and post-construction for the life of the building 4D models are mainly used to (Cory, 2001):

- Facilitate the evaluation, implementation, and monitoring of design changes,
- Evaluate material and equipment accessibility,
- Evaluate and develop the most effective material staging and handling procedures for the project,
- Visualize construction processes.

4D models allow design and construction professionals to test different design and execution sequencing alternatives. A virtual object-oriented 4D models has the potential
to support automated constructability and assist a project team in identifying
constructability issues early in the design and construction phases (Staub and Fischer,
1998). Another advantage of using 4D models can be the effective training and
communication with construction crews specially before engaging in any difficult or
challenging activity for a new construction method or technique. Monitoring the progress
of any given project by comparing as-planned with as-built can be more accurate and fast
(Hartmann and Fischer, 2007). Just-in-time material deliveries are an important aspect on
construction sites where space is at a minimum. In this situation, 4D models can help the
engineers visualize space allocation throughout all building spaces.

Using 4D modeling, the processes of building construction can be demonstrated before
any real construction activities occur (Kunz and Fischer, 2007). This will improve the
identification of possible mistakes or conflicts done unknowingly at an early stage of a
construction project, and thus enables project stakeholders to optimize the construction
schedule as much as possible (Lee et al., 2005).

II.4 INTEGRATED PROJECT DELIVERY APPROACH

Integrated Project Delivery (IPD) is a technological evolution coupled with
owners’ increasing demand for more effective processes that result in a faster; less costly
and less adversarial construction projects. It is not the purpose of this research to
elaborate and discuss the whole new IPD approach. This topic is introduced here only to
focus on a single concept related to the effect of early involvement of contractors during
conceptual design phase. The following sections will describe the concept and the
benefits of using IPD approach and BIM tools to facilitate constructability implementation. All the literature presented is based on the work of The American Institute of Architects (AIA) report entitled "Integrated project Delivery: A Guide"; version 1 (AIA, 2007).

II.4.1 IPD Concept and Benefits

AIA defines IPD as "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction". Recent studies document inefficiencies and waste in the construction industry due to the lack of proper integrations of efforts between various stakeholders. IPD is built on collaboration, which in turn is built on trust since a trust-based collaboration encourages parties to focus on project outcomes rather than their individual goals. The main recorded benefits for using IPD approach in construction projects are:

- facilities managers, end users, contractors and suppliers are all involved at the start of the design process,
- all communications throughout the process are clear, concise, open, transparent, and trusting,
- designers fully understand the ramifications of their decisions at the time the decisions are made,
- risk and reward are value-based and appropriately balanced among all team members over the life of a project,
• A higher quality and sustainable built environment is delivered to the industry.

All in all, IPD influences early contributions of knowledge and expertise through deployment of new technologies, allowing all team members to better realize their highest potentials while expanding the value they provide throughout the project lifecycle.

II.4.2 IPD VS. DESIGN – BUILD

Design-Build (DB) delivery method is characterized by a single point of responsibility for both design and construction activities. The owner often chooses DB to transfer risk and coordination effort to one contractual entity and to assure a higher level of coordination. The owner’s rôle in DB is heavily required in defining the project criteria, followed by less management later on as the design-builder executes the project in conformance with the established owner’s criteria. Although IPD and DB are very similar when applied in this manner, under traditional DB, the owner usually participates through completion of the design and then seeks to minimize input and involvement to define aspects of responsibility and risk regarding all team members. Shifting to IPD is mostly a matter of adding clarity of roles and scope of service to the contract rather than altering the fundamental structure of the DB agreement. Inclusion of additional early participants and their roles and responsibilities should be clearly stated. Requirements for design consultants to collaborate, transfer model data and incorporate input from related trade contractors and vendors should also be added. Costing under the traditional DB agreement is usually early fixed in the form of a Guaranteed Maximum Price (GMP) or lump sum, with most of the risks borne by the design-builder. Another asset for IPD over
BD is that full collaborative efforts and communications between stakeholders can be achieved before costs are finalized and GMP is defined. Figure II-7 shows “MacLeamy Curve” which illustrates the impact of making design decisions earlier in the project when opportunity to influence positive outcomes is maximized and the cost of changes minimized, especially as regards to the designer and design consultant roles. Figure II-8 compares traditional delivery to IPD delivery, focusing on the shifts of when different aspects of the project are resolved and when different project participants’ become involved. All the new phases’ terminologies are introduced by the AIA (AIA, 2007).

![MacLeamy Curve](image)

**Figure II-7: MacLeamy Curve (Construction User Roundtable, 2004)**
II.4.3 IPD AND BIM

The use of BIM as an early integrated model of inputs from constructors, installers, fabricators and suppliers along with designers can results in maximum benefits. Through early collaboration and the use of BIM technology, a more integrated, interactive, virtual approach to building design, construction and operation is emerging. Since BIM is a digital, 3D model linked to a database of specific project information, it is considered as one of the most powerful tools supporting IPD. BIM is a tool, not a project delivery method, but IPD process methods compliment BIM and improve its capabilities. The IPD project team uses BIM to reach an understanding regarding how the project-model will be developed, accessed, and used, and how information can be exchanged between
building systems and stakeholders. In addition to shifting design decision making forward, redefinition of phases in an IPD approach is driven by two key concepts:

- Early integration of all stakeholders during the design phase
- The ability to model and simulate all project data accurately using BIM tools.

The results are a well defined and coordinated project with a much higher level of achievement than a typical level with traditional delivery methods and thus, enabling a more efficient construction process and a potentially shorter construction period. Figure II-9 explores some of the features and possible interrelations between different building aspects and analysis by using BIM in an IPD approach. This research will focus only on constructability assessment using BIM models in an IPD approach.

Figure II-9: BIM Roadmap in an IPD Approach (Krygiel et al., 2008)
II.4.4 Roles of Designers and Contractors in IPD Approach

Implementing the new concepts of IPD using BIM tools will have positive impacts on designers and contractors from a construction process point of view. From a designers’ perspective, an integrated project delivery process allows them to benefit from the early contribution of constructors’ expertise during the design phase. More accurate budget estimates can be exported from the design team to help establish design decisions and pre-construction resolutions of design-related issues. This act will result in an improved project quality and financial performance. Although the IPD process increases the level of effort during early design phases, the payback can be in the reduced documentation time, improved cost control and budget management. Moreover an IPD approach increases the likelihood that project goals, including schedule, life cycle costs, quality and sustainability, will be achieved.

As for the contractor’s side, the integrated delivery process allows constructors to share their expertise in construction techniques early in the design process resulting in an improved project quality and financial performance during the construction phase. The constructor’s participation during the design phase improves:

1. pre-construction planning,
2. the understanding of the design in a more timely and informed manner,
3. the anticipation of design-related issues,
4. the visualizing of construction sequencing prior to construction start, and
5. Cost control and budget management.
All of these benefits increase the likelihood that project goals, including schedule, life cycle costs, quality and sustainability, will be achieved as planned. The constructor’s role will be increased in a significant way during early stages of design, in which they now provide strategic services such as schedule production, cost estimating, phasing, systems evaluation, and constructability issues. While in traditional project delivery methods, the timing of these services is done after the design phase is finished.

As for contracts, decisions are also made and documented regarding the level of details to be modeled. The BIM model will offer the platform required to generate specific data such as cost data, material quantities, and components’ specifications and so on… It is at this point that IPD approaches can distinguish two kinds of contracts: a final contract document and a preliminary one. If the model serves the preliminary contract document, then clear and explicit definitions of incentive milestones and project details will be introduced before agreeing on the final project scope. After the involvement of the project stakeholders in all project revisions, the final contract will define the ultimate project specification and duties of all the involved members. That is why IPD contracts can be more complex than traditional construction contracts.

II.5 MULTI-CRITERIA DECISION-MAKING

II.5.1 SIMPLE MULTI-ATTRIBUTE RATING TECHNIQUE (SMART)

Multi-Attribute Utility Theory (MAUT) is a quantitative comparison method used to combine dissimilar measures along with individual and stakeholder preferences, into high-level, cumulative preferences. The foundation of MAUT is the use of utility
functions. Utility functions are functions that transform unlike criteria to one common dimensionless scale (0 to 1) known as the multi attribute “utility”. Once utility functions are created, an alternative’s raw data (objective) or the analyst’s beliefs (subjective) can be converted to utility scores. Utility functions are typically used, when quantitative information is known about each alternative, which can result in firmer estimates of the alternative performance (Edwards and Barron, 1994).

The Simple Multi Attribute Rating Technique (SMART) can be a useful alternate of the MAUT method. This method utilizes simple utility relationships. Five, seven, and ten point scales are the most commonly used. The SMART methodology allows the use of less of the scale range if the data does not distinguished effectively. When actual numerical data are unavailable, subjective reasoning or opinions can be substituted and documented in the final report instead. Research has demonstrated that simplified MAUT decision analysis methods are robust and replicate decisions made from more complex MAUT analysis with a high degree of confidence are achievable (Goodwin and Wright, 1998).

II.5.2 ANALYTIC HIERARCHY PROCESS (AHP)

The Analytic Hierarchy Process (AHP), which was developed by Professor Thomas Saaty, is an analytical tool using a deductive approach (Wong and Wu, 2002). The technique structures a decision problem into a hierarchy of criteria, sub-criteria and alternatives, followed by a series of pair wise comparisons to derive prioritized scales. First, the decision is structured into a hierarchy of goals, criteria and alternatives. Having
structured the problem, pair wise comparisons are carried out among all the criteria with respect to the goal. These comparisons will derive the local priority ratios as proxy of the priority vectors for the criteria. These pair-wise comparisons are made using a nine-point scale (Saaty, 1994):

1 = Equal importance or preference
3 = Moderate importance or preference of one over another
5 = Strong or essential importance or preference
7 = Very strong or demonstrated importance or preference
9 = Extreme importance or preference

Consistency Ratios (CR) are computed for measuring the consistency of judgments. The use of the AHP basically serves 2 purposes: assigning weights to a set of predetermined criteria or measures; and prioritizing or ranking elements to identify the key elements (Cheng and Li, 2002). The “priority vector” (i.e. the normalized weight) is calculated for each criterion using the geometric mean of each row in the matrix divided by the sum of the geometric means of all the criteria. According to Saaty (1995), the priority vectors can be calculated by multiplying the "n" judgments in each row and taking the n\textsuperscript{th} root, followed by normalizing the resulting numbers. This process is then repeated for the alternatives comparing them one to another to determine their relative value/importance for each criterion. The calculations are easily established in a spreadsheet, and commercial software packages, which are currently available (Edwards and Barron, 1994).
The AHP method has been widely applied in various fields of the building industry such as facility management benchmarking (Gilleard and Wong, 2004), asset management (Tran et al., 2003), piles productivity (Zayed and Halpin, 2004), procurement selection (Al-Khalil, 2002), contractor selection (Fong and Choi, 2000), project management (Al-Harbi, 2001) and maintenance management (Shen et al., 1998).

II.6 PREVIOUS AND RELATED WORK

As stated previously in section II.2, quantified assessment of design is the best approach to improve constructability. The existing principles of quantifying constructability of design can be evaluated with respect to 6 dimensions: (i) Representation; (ii) Comprehensiveness; (iii) Objectivity; (iv) Ease of understanding; (v) Ease of operation; and (vi) Support for continuous constructability improvement (Wong et al., 2007). The following section discusses in details the previous works done by different researchers concerning constructability assessment.

II.6.1 STUDIES ON ASSESSING CONSTRUCTABILITY OF DESIGNS

In the Asian arena, Singapore has pioneered in the field of quantifying constructability based on a scheme known as the Buildable Design Appraisal System (BDAS). Under the Building Control Act (BCA), legislation was passed for the enforcement of the minimum constructability score making such a score a prerequisite for plan approval with effect from 2001. The concept is based on a “3S” design principle in which a design is tested for constructability issues with respect to Standardization, Simplicity and Single Integrated Elements. The constructability scores are given
according to the relative extent of labor saving during construction. With respect to this philosophy, designs with higher scores are generally more buildable and fewer site workers are needed if carried out by the same contractor (BCA, 2005 a-b-c). Details for the assessment method used in the BDAS are found in the appendix A.1. A similar approach was used for assessing constructability proposed for the Hong Kong construction industry in 2007 through a PHD thesis by Wong (Wong, 2007) and it is found in appendix A.2.

Another constructability multi-attribute system (BMAS) was developed for assessing constructability of designs in Malaysia in 2004. The assessment is based on 6 principles with identified factors for each principle which are developed through a literature review, questionnaire survey and brainstorming sessions. The six principles are:

1. Design for simple assembly
2. Encourage standardization and repetition
3. Design for prefabrication, preassembly or modularization
4. Analyze accessibility of the jobsite
5. Design for the available skills
6. Consider suitability of designed materials.

This developed constructability framework is based on series of brainstorming sessions. This system incorporated only the previously 6 constructability factors. The assessment criteria are based on quantitative quantities from the selected design and mathematical formulas. Based on these details, the interpretation of the overall result of constructability
levels were achieved through a five point scale: (Very Poor, Poor, Medium, Good or Very Good). This scale represents some defined quantifiable values for each constructability factor (Zin et al., 2004). Details for this assessment method are found in appendix A.3.

Another assessment method was based on cognitive models (CM) and was proposed for constructability assessment for steel frame structures (Ugwu et al., 2004). The concept, found in appendix A.4, is based on the use of interviewing techniques to understand problem solving and the development of knowledge models for automated constructability assessment. The knowledge models organize intelligent agents for constructability assessment during design stages, and facilitate the agent development process through direct participation of the domain expert who teaches the agents how to solve such problems. Deep knowledge mining and protocol analysis were used to identify constructability issues and develop decompositions of the cognitive tasks associated with problem solving in the domain (Ugwu et al., 2004). Yang developed a fuzzy Quality Function Deployment (QFD) system to support constructible design decision making. It adapted the House of Quality (HOQ) to provide a systematic and structured method to support the integrated decision-making process of constructible designs, and applied a fuzzy set theory into HOQ to facilitate the processing of design-relevant QFD information. In this system, the fuzzy set theory is integrated into HOQ to capture the inherent imprecision and vagueness of design-relevant inputs and facilitate the analysis of design-relevant QFD information (Yang et al., 2003). Details for this assessment method are found in appendix A.5.
II.6.2 Comparison and Limitations of Previous Studies

The previous section discussed several studies that worked on developing a quantification approach for constructability of design. Table II-1 summarizes a comparison between the before mentioned studies and focuses on limitations found. It is quite obvious that time factor was not included in any of the previous work. The analysis of the time module throughout all construction phases is essential for any constructability evaluation (Hartmann and Fischer, 2007).

<table>
<thead>
<tr>
<th>Studies on constructability assessments of design</th>
<th>Assessment concept based on</th>
<th>Assessment methodology</th>
<th>Assessment benefits</th>
<th>Assessment limitation</th>
</tr>
</thead>
</table>
| Buildable Design Appraisal System (BCA, 2005)    | - Standardization           | Mathematical model to calculate overall constructability value | - Reduces reliance on foreign workers | - Needs governmental benchmark 
- Time factor is not included. |
|                                                  | - Simplicity                |                        |                     |                      |
|                                                  | - Single integrated element |                        |                     |                      |
| Empirical System for Scoring Constructability (Wong, 2007) | BCA, 2005                   | Mathematical model to calculate overall constructability value | - More factors are included in the assessment than the ones presented in BCA, 2005 | - Needs governmental benchmark 
- Time factor is not included. |
| Constructability Assessment Framework (Zin et al., 2004) | - Simple assembly           | Mathematical formulas are established for each constructability aspect | Assists designers and contractors in efficient constructability evaluation | - Time factor is not included 
- All factors are independent from each other and no formal criteria is presented to evaluate the whole design in a single result. |
<table>
<thead>
<tr>
<th>Cognitive Models for Constructability Assessment (Ugwa et al., 2004)</th>
<th>Constructability issues as identified by protocol analysis</th>
<th>A knowledge model which deploys intelligent agents in constructability assessment during design stages</th>
<th>Enhances the analysis synthesis, storage, management of knowledge in solving design problems</th>
<th>-The whole system is based on knowledge mining protocol and not on design components. -It deals with tasks rather than objects.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuzzy Quality Function Deployment System (Yang et al., 2003)</td>
<td>Client and constructability requirements -Characteristics of building components -Client satisfaction index -Constructability satisfaction indices</td>
<td>Fuzzy Quality Function Deployment model</td>
<td>The system supports decision making for quantitative constructability evaluation</td>
<td>Very complex modeling system -Demanding assessment measure -It needs a lot of input rules</td>
</tr>
</tbody>
</table>

Any attempt to neglect the time factor will eliminate the possibility to evaluate many essential constructability attributes like: sequence of installed components, space allocations, weather effect, etc...Mathematical models need a continuously updated benchmark in order to evaluate their result. The BCA system which is implemented in Singapore is completely dependent on the indexes and rates supplied by governmental institutions to the construction industry. This system cannot be applied in countries that do not have such an equivalent benchmark.

As for fuzzy and knowledge protocol based models, the common limitation to their uses is that both methods are not based on building components. From a designer and a contractor point of view, building components are the prime bases for data evaluation and revisions. The absence of object-based models will make any constructability assessment difficult especially for junior designers or for seniors who finds fuzzy concepts difficult to handle.
II.7 SUMMARY

This chapter reviewed several topics that gave an overview on how to approach the stated problem. First of all, constructability concept was discussed with a focus on the different approaches to improve its implementation during the design phase. Then, 2 new approaches in the A/E/C industry were presented: building information modeling and integrated project delivery approach. The aim was to clarify the possibility of constructability improvement by the use of these new advances in the A/E/C industry. Decisions making techniques like AHP and SMART were identified briefly since the assessment method will be based on these 2 concepts. Symptoms of poor constructability of designs were also analyzed. Lack of communication between contracting parties, segregation of design and construction, inadequate contractor's inputs at the design stage and the inefficiency of the design process are the main findings of bad constructability. Constructability implementation is encouraged during the design stage, which is the most suitable time for implementing constructability measures as to enable efficient construction. The whole concept for applying constructability principles is to minimize the gap between designers and contractors as to solve any anticipated constructional difficulties and on-site logistics before physical construction starts. The best approach to improve constructability of design is to assess its application in design. Several studies on assessing constructability were discussed and 4 main limitations were recorded:

- Time factor was not presented
- Independency on building object
- Dependency on governmental benchmarks’
- Complex modeling
BIM technology and IPD process were discussed in detail in order to pave the way for a proposed methodology based on integrating these 2 concepts with decision making techniques to assess the constructability of designs. Based on this extensive and exhausting literature review, it is clear that there is a tremendous need to improve constructability of designs using an object oriented models like BIM in an integrated delivery process like IPD.
Ch III. Research Methodology

As previously before, the intention of this research is to develop a new constructability assessment platform for building designs. The prospective assessment method has to take into consideration the limitations recorded in previous works and address new challenges that awaiting the A/E/C industry. From this perspective, the research methodology that addresses this concern is built as shown in Figure III-1. The following sections illustrate briefly the rationale behind each phase in the proposed methodology.

III.1 LITERATURE OVERVIEW

Based on the work of the Construction Industry Institute (CII) in the field of constructability knowledge, 8 design-relevant principles are recorded. These principles are (CII, 1986):

- Basic design approaches consider major construction methods such as modularization or preassembly.
- Modular/preassembly designs are prepared to facilitate fabrication, transportation, and installation.
- Design elements are standardized including maximum use of manufacturer’s standards and standardized components.
- Designs are configured to enable efficient construction considering issues like simplicity, flexibility, sequencing of installation, and labor skill and availability.
• Construction efficiency is considered in specification development including prior review of specs by construction personnel.

• Designs promote construction accessibility of personnel, materials, and equipment.

• Designs facilitate construction under adverse weather.

• Design and construction sequencing facilitates system turnover and start-up.

From these principles, all design-relevant factors affecting constructability of design will be identified. Attributes and values for these factors will form the constructability input for designers to be used during the design development. Topics related to BIM, 4D models and IPD approaches will be also be studied to figure out how the advancement of these technologies and techniques can help solve the identified problem statement.

III.2 DATA COLLECTION

Data collection starts by a survey questionnaire to assess the relative importance of the selected factors and assign weights to them. The survey results are discussed in detail in section IV.1.2. The survey was forwarded to experienced professionals in the field of design, construction and management disciplines. The relative weight of each factor was calculated using Analytical Hierarchy Process (AHP) technique and imported to the model. These factors are discussed in detail in section IV.1. Another important aspect that was studied in the literature review was the rationale used for developing the evaluation criteria that would assist the design team in their subjective evaluation of their design proposals. These criteria will aid the designers to rate the output data from BIM and 4D models using a scale that ranges from very bad to very good. Evaluation schemes and rating rationale will be introduced in section V.4.
Figure III-1: Research Methodology
III.3 INTEGRATING BIM AND CONSTRUCTABILITY

As discussed in the literature review chapter (section II.1.7), integration of BIM components with constructability concepts and principles can facilitate data organization and thus yields to a better design analysis concerning constructability. Identified constructability factors will be added to design components as shared data attributes so that the designer can specify particular constructability inputs for each design family or component. These attributes in addition to others (quantities, specifications, trades, etc...) will be exported from the BIM model to an Access data model and linked to their relative constructability categories where the analysis process will take place. Figure III-2 shows classification of constructability tools as presented by Fisher (2007) and the proposed relationship with BIM tools.

![Diagram of Constructability Tools]

Figure III-2: Integration of BIM and Constructability Adopted from (Fisher, 2007)
III.4 CONSTRUCTABILITY EVALUATION SCHEME IDENTIFICATION

Constructability factors cannot be easily evaluated by traditional measurement methods or mathematical models due to their qualitative or subjective nature. In order to establish a practical evaluation scheme to evaluate these factors, two main principles must be relied on: general constructability rules and project specific rules. General constructability knowledge will be collected from literature reviews and published journal papers and they will represent the generic rules criteria. As for the project specific rules, each factor will have specific rating criteria relative to project stakeholders’ standards and experience. These project rules cannot be generic or standardized since each project is unique, and constructability is subjective from one team to another. The flexibility of the proposed rating and evaluation schemes will address this problem. Using SMART application technique, rating criteria will be converted to utility values that will be incorporated in the assessment model. Figure III-3 shows the roadmap that will be used to establish the before mentioned rating criteria.

![Diagram](image.png)

**Figure III-3: Evaluation Scheme Overview**
III.5 ASSESSMENT MODEL

The assessment calculation is based on the combination of two different decision making techniques AHP and SMART and as per the process presented in Figure III-4. A questionnaire survey was used to collect construction experts’ feedback concerning relative importance of constructability factors. Based on AHP technique, these feedbacks were used to calculate the relative weights (W) of factors incorporated in the proposed model. SMART technique was used in the proposed methodology as per the evaluation scheme proposed in section III.4 to generate utility values (U) for each identified factor. Constructability indexes (C₁) are calculated by multiplying the factor weight with its corresponding utility value. The total constructability score (C₁) is the summation of all of the 16 factors incorporated in the model. The final generated score represents the overall level of constructability satisfaction in a particular building design. In other words, the score answers the question of: What is the implementation percentage of constructability rules in a particular building design. The score can be interpreted as per the following two different scenarios:

- In case of more than one design alternative is presented, the building with the highest constructability score will be the most preferable, since it meets the constructability requirements of the design team more than the others.

- In case of a single design proposal, the final score will measure the overall level of constructability implementation with respect to the project’s specific requirements. Based on this final score, the project team will decide whether to accept the design as it is proposed or apply any needed modification. The design can be reassessed until maximum possible score is achieved.
Figure III-4: Integration of AHP and SMART in the Assessment Model

Figure III-5: Utility Value Scale
III.6 Model Implementation

This section will explain how the model was implemented to calculate constructability score of design. Two main issues are addressed here: when the model will be used, and how to run the model until maximum possible constructible score is achieved. As discussed earlier, the constructability analysis will start in the preconstruction phase and specifically during the criteria design and detailed design phases. Figure III-6 shows the proposed framework of the steps involved in testing the design virtually to achieve maximum constructability. Using Revit Architecture © 2009 the design will be generated as a BIM model where all available construction data will be linked to their corresponding 3D components. Preliminary time schedule using Microsoft Project © will be linked to design components to establish a 4D model which will be used to test for several time related factors like proper installation sequence components.

This research emphasizes the implementation of this procedure throughout an IPD approach where the main contractor will be involved in early stages of the design phase and not at the end of the design phase. The finished BIM and 4D model will be used as an output engine for various constructions data mainly: drawing sets, bill of quantities (BOQ), building cost, components’ specifications, windows/ doors schedule, space allocation, construction sequence, etc...Quantitative data will be automatically exported from Revit to the Microsoft Access © 2007 database where the constructability analysis will take place. As for analyzing the time schedule effect on the design, snap-shots from the 4D simulation model will be exported using NavisWorks © 2009. Data from Revit in addition to 4D snap-shots will be linked to their corresponding constructability factors where the user, which is the design team in addition to the contractor, will evaluate them.
based on a 5 point scale from very bad to very good. A rating criterion will be provided to each factor as to assist the user in his/her evaluation as discussed in section III.4.

Figure III-6: Model Implementation Methodology Using an IPD Approach
Constructability score is calculated based on the framework proposed in section III-5. All of the calculation process will be done automatically as long as the user identifies the utility values. If the constructability score is not accepted, the design team will go back to the original BIM model and modify the components. Factors that have a low constructability index $C_1$ reflect a low constructability implementation. This process can be repeated as much as the user wants until the maximum possible score is achieved; only then the design can proceed to the next phase.

### III.7 Tool Development

An application tool was developed to implement the proposed model. The application was based on MS© Access 2007 and contains 16 user-friendly interfaces for each of the 16 constructability factors in addition to reports’ interfaces. Each interface page contains the entire attributes exported from BIM that are linked to their corresponding constructability factors. These attributes cannot be changed within the Access file unless they are modified from the main BIM model. Data extracted from the 4D model is presented in the form of a simulation movie or snap-shots pictures where the user can see the virtual construction of the building or analyze working space allocation at any given time. The design team will evaluate the data provided from BIM or 4D models and assign a utility value based on the evaluation criteria scale provided. Constructability scores will be calculated automatically. Any modified data done to the original BIM model will be imported directly to the assessment tool and thus the final constructability score will be instantly adjusted based on the new added inputs.
III.8 SUMMARY

This chapter explained briefly the main phases of the proposed methodology. The methodology starts with a literature review, followed by a section that explains how BIM and 4D model are integrated with constructability principles. Evaluation schemes along with rating criteria needed to assist the user in evaluating constructability factors are also explained. The new methodology for developing and implementing the assessment model was introduced in this chapter. The final section explained briefly the user friendly Access-based tool used to run the proposed framework.
Ch IV. Data Collection

The data collection phase consists of four stages which are required to develop and run the proposed constructability assessment platform. In stage one, factors incorporated in the model are identified and then weighted. Stage two describes the procedure used to identify the data from BIM and 4D models. Stage three, explains the steps followed to establish the new constructability evaluation schemes. Stage four in this chapter discusses the collected data needed to demonstrate the case study presented in V.9. The process of data collection and its parts are shown in Figure IV.1.

![Data Collection Process Diagram]

Figure IV-1: Constructability Assessment Model Data Collection Process

IV.1 FACTORS IDENTIFICATION

This section will focus on three points needed to set-up the factors incorporated in the model: factors’ identification, factors’ relative weight and statistical analysis to
evaluate their recorded values. Factors' weights are based on the outputs of a questionnaire survey and the factors' identification is based on the literature reviews and published papers. The three parts of the factors' identification process are as follows:

**IV.1.1 FACTORS INCORPORATED IN THE MODEL**

Relying on literature reviews and published journal papers as well as scientific and academic reports, factors affecting constructability of designs are studied and recorded in this section. Based on the 8 design-relevant constructability principles reported by the CII and stated in section III.1, categories, sub-categories and factors are classified as shown in table IV-1 in accordance to 3 main levels. Level #1 contains the 3 main categories that form the umbrella of all factors affecting constructability of design. Level #2 contains the sub-categories that constitute factors incorporated in the model. Level #3 includes those factors that are weighted and used to develop and run the model.

Table IV-1: Constructability Factors Incorporated In the Model

<table>
<thead>
<tr>
<th>Level #1</th>
<th>Level #2</th>
<th>Level #3</th>
<th>Relation to Constructability Concepts</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Attributes</td>
<td>Standardization</td>
<td>Prefabrication</td>
<td>Precast Concrete, Prefabricated utility products, etc...</td>
<td>Ferguson, 1989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Grid Layout</td>
<td>Horizontal / Vertical / Radial Grid dimensions</td>
<td>BCA, 2005</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Standard Dimensions</td>
<td>Dimensions for door, windows, partitions, tiles, etc...</td>
<td>Griffith and Sidwell, 1997</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dimensions for door, windows, partitions, tiles, etc...</td>
<td>Dimension of building elements should reflect material sizes and should be designed to minimize labour requirements and wastage of material by special cutting</td>
<td></td>
</tr>
<tr>
<td>Construction Attributes</td>
<td>Resources' Availability</td>
<td>Accessibility of materials or special equipments.</td>
<td>Designers should use widely available materials that can be economically feasible.</td>
<td>Ferguson, 1989</td>
</tr>
<tr>
<td>------------------------</td>
<td>------------------------</td>
<td>--------------------------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>-------------</td>
</tr>
<tr>
<td></td>
<td>Labour's Skills</td>
<td>Availability of special labour skills</td>
<td>Designs should improve constructability by designing for economical use of available skilled workers.</td>
<td>Griffith and Sidwell, 1997 Nima et al., 1999</td>
</tr>
<tr>
<td></td>
<td>Construction Sequence</td>
<td>Sequence of installation of components.</td>
<td>Appreciating the sequence of operations and trade interrelationships on site can enhance constructability of design.</td>
<td>Griffith and Sidwell, 1997</td>
</tr>
<tr>
<td></td>
<td>Time under Ground</td>
<td>Construction time under ground level.</td>
<td>Reducing the construction time below ground level can improve constructability.</td>
<td>Adams 1989</td>
</tr>
<tr>
<td></td>
<td>Building Envelope</td>
<td>Construction of the whole building envelope.</td>
<td>Designers should facilitate the enclosure of building at the earliest possible stage to exclude hind rage and damage because of bad weather</td>
<td>Adams, 1989 Nima et al., 1999</td>
</tr>
<tr>
<td></td>
<td>Weather Effect</td>
<td>Effect of climate conditions on construction work.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Safety</td>
<td>Effect of construction sequence of workers' safety.</td>
<td>The design should be arranged so as to facilitate safe working in foundations and earthworks.</td>
<td>CII, 1986</td>
</tr>
<tr>
<td></td>
<td>Material Access</td>
<td>Space for material storage and transportation on site.</td>
<td>The efficient location and distribution of temporary works and storage areas are necessary for good buildability</td>
<td>Ferguson, 1989 Nima et al., 1999</td>
</tr>
<tr>
<td></td>
<td>Personnel Access</td>
<td>Accessibility of equipments and tools for and from different site locations.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure IV-2 shows the hierarchy used for the 16 factors. The presented hierarchy will be used for the survey questionnaire and throughout all the phases of this research.
IV.1.2  Relative Weights of Factors

The before identified constructability factors in section IV.1.1, are relatively weighted using the AHP technique and based on the responses gathered from a survey questionnaire done throughout different Canadian provinces. The questionnaire; Figure IV-3; was sent to sixty-two experts (architects, designers, consultants), however feedback was received from only fifteen, giving a low response of 24%. Geographically, the received responses can be summarized as per Figure IV-2. At this point the relative weight of each factor at each level of the hierarchy is collected. This could be the answer to the question of “What is the importance of each factor in contributing to impact on constructability?” The questionnaire survey asked the participants to perform a pair wise comparison for each factor found under each level. They were provided with a 9 point scale that ranges from “Equally Preferred” to “Extremely Preferred” as proposed by Saaty (1994). The sample form was designed in a very simple manner as to record the experts’ opinion concerning importance of factors affecting constructability easily. All the factors recorded in level #3 are categorized with respect to their main category so that the respondent performs their rating with respect to these specified categories. For example: flexibility, resources availability and skills labors’ availability are 3 factors found in the sub-category “economical impact of design” which falls in under the main category “Design Attributes”. Thus pair wise comparisons will be made throughout these 3 levels separately:

1. Level #1: main categories
2. Level #2: sub-categories
3. Level #3: factors
Figure IV-3: Survey Questionnaire Sample

Figure IV-4: Distribution of Responses among Canadian Provinces

Based on the 15 received responses, pair wise comparison matrixes are developed for each hierarchy level based on the AHP methodology proposed by Saaty (1994). After performing all the needed matrices, the weight of each factor is calculated by multiplying
its local weight by the weight of its up-level sub-factor. The final weight of each factor is the average of weights of all the 15 responses are recorded in table IV-2. For the purpose of this research, the final calculated factor weight will be named as “factor weight”.

Table IV-2: Constructability Factors' Weight

<table>
<thead>
<tr>
<th>Level #1</th>
<th>Weight</th>
<th>Level #2</th>
<th>Weight</th>
<th>Level #3</th>
<th>Weights</th>
<th>Decomposed Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Attributes</td>
<td>0.667</td>
<td>Standardization</td>
<td>0.788</td>
<td>Prefabrication</td>
<td>0.575</td>
<td>0.302</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Grid Layout</td>
<td>0.282</td>
<td>0.148</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Standard Dimensions</td>
<td>0.143</td>
<td>0.076</td>
</tr>
<tr>
<td></td>
<td>Economical Impact</td>
<td>0.212</td>
<td>Components' Flexibility</td>
<td>0.611</td>
<td>0.086</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Resources' Availability</td>
<td>0.172</td>
<td>0.025</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Labour's Skills</td>
<td>0.216</td>
<td>0.031</td>
<td></td>
</tr>
<tr>
<td>Construction Attributes</td>
<td>0.181</td>
<td>Installation</td>
<td>0.514</td>
<td>Construction Sequence</td>
<td>0.514</td>
<td>0.048</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Time under Ground</td>
<td>0.087</td>
<td>0.008</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Building Envelope</td>
<td>0.123</td>
<td>0.011</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Weather Effect</td>
<td>0.151</td>
<td>0.014</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Safety</td>
<td>0.125</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Accessibility</td>
<td>0.486</td>
<td>Material Access</td>
<td>0.605</td>
<td>0.053</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Personnel Access</td>
<td>0.214</td>
<td>0.019</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Equipment Access</td>
<td>0.130</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Site Impacts</td>
<td>0.152</td>
<td>Adjacent Structures</td>
<td>1.000</td>
<td>To Adjacent Foundation</td>
<td>0.720</td>
<td>0.110</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>To Infrastructure</td>
<td>0.260</td>
<td>0.043</td>
<td></td>
</tr>
</tbody>
</table>

Figure IV-5 shows a graph of the relative weights of constructability factors. As per this graph, prefabrication factor has shown the highest value based on the fact that design attributes showed the highest ranking. The lowest ranked factor is found to be time underground which means that it has minimum impact on constructability. These weights
will be essential for running the model as their respective values will have a direct impact on the overall constructability score.

![Constructability Factors Relative Weights](image)

Figure IV-5: Constructability Factors Relative Weights

IV.1.3 **Statistical Analysis of the Survey Results**

The following measurements of the statistics were undertaken to analyze the collected data:

1. **Reliability analysis**: to estimate the reliability of the questionnaire responses.

2. **Consistency ratio**: to express the internal consistency of the judgments that have been entered.

Cronbach’s alpha is the most widely used measure of reliability (Wei *et al.*, 2007). Cronbach’s alpha ($\alpha$) is an index used to estimate the reliability of a scale containing several items. The closer ($\alpha$) is to 1.00, the greater the internal consistency of the items in
the instrument being assessed; (α) will generally increase when the correlations between the items increase. The lower acceptable limits of (α) are 0.50 and 0.60 were suggested by Kaplan and Saccuzzo (1993). The purpose of this test is to check whether the scale values achieved from the survey are reliable or not. Attributes “accessibility” and “installation sequence” showed a low reliability coefficient but within acceptable range (0.5 < α < 0.6) and thus their results were included in the model. The complete (α) values for the reliability analysis are shown in Table IV-3.

Table IV-3: Reliability Analysis

<table>
<thead>
<tr>
<th>Main Attributes</th>
<th>Cronbach’s (α)</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standardization</td>
<td>0.949</td>
<td>High</td>
</tr>
<tr>
<td>Economical Impact</td>
<td>0.651</td>
<td>High</td>
</tr>
<tr>
<td>Accessibility</td>
<td>0.572</td>
<td>Low (within acceptable range)</td>
</tr>
<tr>
<td>Constructability Consideration</td>
<td>0.866</td>
<td>High</td>
</tr>
<tr>
<td>Effect on Constructability</td>
<td>0.624</td>
<td>High</td>
</tr>
<tr>
<td>Installation Sequence</td>
<td>0.596</td>
<td>Low (within acceptable range)</td>
</tr>
</tbody>
</table>

The next part of the data analysis process is to check the internal consistency of the judgments that have been entered to the AHP matrix calculations. Consistency Ratio (CR) calculations are performed on all weights to identify how consistent the values are. Saaty (1994) proved that for consistent reciprocal matrix, the largest Eigen value is equal to the size comparison matrix. He then gave a measure of consistency, called Consistency Index as deviation or degree of consistency using the CR formula. All (CR) calculations
were found to be within acceptable limits, and thus the factors' weights were then incorporated in the proposed model.

**IV.2 CRITERIA RATIONALE FOR EVALUATION SCHEMES**

Since constructability is a knowledge based abstract, stakeholders will always have different interpretations on how to understand its impact on design. From this sense, what seems easy to construct for a particular construction team, may be difficult for another team. In other words, contractors may execute the work in different manners, but at the end they have to follow a generic construction knowledge based on a specific rationale to get the work properly done. From this perspective, each factor presented in the model is provided with specific rationale criteria in order to assist the user in rating the various constructability factors. These rationales are extracted from the literature and published journal papers. This research proposed 16 different rationale criteria list as to meet the concepts of the 16 identified constructability factors. All of the attributes presented in the section will be integrated in the BIM model or identified from the 4D model so that the designer will input the values of these attributes the moment the individual starts designing his/ her project. The following sections will describe the rationale attributes proposed for each factor.

- Prefabrication: Prefabrication can have a direct positive impact on three main construction drivers, cost, schedule and workforces issue. It also increase craft productivity, improve quality, and reduce labor rates (Hass et al., 2000). From a constructability point of view the more fabricated components are involved in the design, the more the positive impact is on constructability. The attributes related to this factor are:
- **Prefabrication**: Prefabrication can be defined as “a manufacturing process, generally taking place at a specialized facility, in which various materials are joined to form a component part of a final installation” (Tatum, 1988). Any component that is manufactured offsite and is not a complete system can be considered to be prefabricated (Hass et al., 2000).

- **Preassembly**: A common definition for preassembly is “a process by which various materials, prefabricated components, and/or equipment are joined together at a remote location for subsequent installation as a unit” (Tatum, 1988). The preassembly process can involve adapting sequential activities into ones that are parallel. Preassembly is generally considered to be a combination of prefabrication and modularization. It may use fabricated components made offsite and then assembled near the site. These units can then be installed at the site, similar to modules (Hass et al., 2000).

- **Grid Layout**: Grid layout plays an important aspect in achieving overall improved constructability. A modularized grid layout facilitates fabrication of components, reduce material waste and make installation sequence faster (Song et al., 2005).

  Attributes related to this factor are:
  
  - **Horizontal Grid**
  - **Vertical Grid**
  - **Circular Grid**

- **Standard Dimension**: this factor checks all components of the buildings if its constitute parts have a standard dimension or not. The attributes are:
- Standard Components
- Custom Made Components

Component Flexibility: Flexibility can be characterized as the ability of a system to cope with unforeseen changes (Schneeweiss and Schneider, 1999). Product flexibility can be defined as the degree of responsiveness (or adaptability) for any future change in a product design. Making a design more flexible leads to a reduction in redesign cost and plays a significant role in responding faster to customer feedbacks by allowing quicker updates in the products and achieving higher levels of performance in a short span of time (Rajan et al., 2005). The 4 main attributes to analyze flexibility of design components are:

- Potential for Change: The user has to identify each component whether a particular component has a potential to change or not.

- Effect of Change: If the component has a potential to change, the user must identify the effect of the change from a 3 point scale; Low, Moderate or High. Otherwise he/she will state NA for not applicable.

- Readiness for Change: If the potential for change was positive, the user must state if the construction team is ready for the change or not. For example, the construction team must identify whether they are ready to change an internal partition 125mm to a 145mm thick with a 2 hour fire rated protection or not.

- Position Flexibility: This attribute addresses flexibility more specifically concerning orientation and horizontal display.
➢ Resources Availability: Availability of resources is considered one of the main factors for addressing constructability of a given design. Resources here mean ordinary labor, material or equipment. That attributes related to this factor are:
  ○ Equipment availability
  ○ Personnel availability
  ○ Material availability

➢ Labor Availability: Labor here stands for a specialized skilled labor or talent. Some activities needs a particular kind of labor and the unavailability of this resource can cause a delay of a construction activity. That attributes related to this factor are:
  ○ Special skill needed
  ○ Special skill unneeded

➢ Construction Sequence: Attributes related to this factor are (Echeverry et al., 1991):
  ○ Physical relationships among components: Building components are spatially restricted; weather protected, or gravity supported by other components. Activity sequencing has to respond to these inter-component relationships.
  ○ Trade interaction: Activity sequencing also responds to different ways in which trades affect each other during construction phase.
  ○ Path interference: Building components have to be moved around jobsite in order to be installed. Activity sequence has to guarantee an interference-free path for installation of any component.
- **Code regulation**: Activity sequencing is also response to construction-phase safety considerations.

  - **Time underground**: must be calculated as its value must be taken in consideration to assess the overall constructability. The attributes used for this factor are:
    - **Total construction time for activities at the underground level**
    - **Total project duration**

  - **Building Envelope**: The study of building envelope can ensure proper enclosure analysis of the project. This factor will be used in the overall constructability assessment. The attributes used for this factor are:
    - **Number of days to finish all external activities**
    - **Total project duration**

  - **Weather Effect**: The 2 attributes needed to analyze this factor are:
    - **Number of days with expected bad weather**
    - **Number of planned dates that match the same bad weather days**

  - **Safety**: Safety issues must be recognized throughout all stages of the design phase (Hinze and Wiegand, 1992). The main important issues to be addressed by designers are:
    - **Hazardous locations**: chemical materials, gas containers or unsafe openings must be well identified as to be prevented when planning for work spaces and material access.
    - **Parapet height**: Height of minimum 42 inch will provide immediate guardrail thus eliminating the need to construct one and improving safety during construction phase.
- **Window sill height**: The same rule applied for parapet height is applied here.

- **Identify components to be fabricated on ground then placed in place**: in order to reduce exposure to falls from elevation and the risk of workers being struck by falling objects.

- **Identify permanent stairways and walkways (have priority to be constructed first)**: to minimize the use of temporary scaffolding.

- **Identify overhead power lines for cranes**: to reduce contact with high voltages.

- **Overtime periods**: overtime periods will reduce the alert of workers during construction.

> **Material Access**: To insure proper material accessibility throughout different site locations, specific space allocations must be properly defined. Diverse space areas based on literature findings are listed here and they will form the main attributes used to analyze the material access factor from any given 4D model (Riley and Sanvido, 1995).

<table>
<thead>
<tr>
<th>Unloading Area</th>
<th>Staging Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage Area</td>
<td>Prefabrication Area</td>
</tr>
<tr>
<td>Working Area</td>
<td>Protected Area</td>
</tr>
<tr>
<td>Material Path</td>
<td>Debris Path</td>
</tr>
</tbody>
</table>

> **Personnel Access**: Similar to the previous factor, 4 attributes are proposed here to insure proper personnel path:
- **Hazardous path**
- **Hazardous locations**
- **Stair cases accessibility**
- **Scaffolding area**

➢ **Equipment Access:** equipment space is defined as a space occupied by a resource or temporary facility which is used to support other activity work elements. The analysis of equipment space can lead to the analysis of the equipment access using these attributes:
  - **Unloading area**
  - **Storage area**
  - **Working area**
  - **Equipment occupied place**

➢ **Effect to Adjacent Foundation:** like adjacent building structures (Basement, retaining walls, foundations, etc...) Two attributes identified for this factor:
  - **Identify exciting adjacent foundation**
  - **Distance between adjacent foundation and new building**

➢ **Effect to Infrastructure:** like adjacent sewage system or underground power line installations. The 2 attributes identified for this factor are:
  - **Identify exciting adjacent infrastructure**
  - **Distance between adjacent infrastructure and new building**

The relationship of these attributes with respect to their usage in the evaluation schemes will be presented in section V.4.2.
IV.3 DATA IDENTIFICATION FROM THE DIGITAL MODELS

To insure proper and accurate output of constructability data to the proposed assessment model, a special technique must be developed to insure proper constructability input to the design. This aspect can be achieved by modifying certain aspects of the BIM and 4D model. The technique also must be generic so that whatever kind of BIM vendor the user is working on, the assessment method can work properly. This section will discuss the technique used to identify the data from BIM and 4D models:

IV.3.1 DATA IDENTIFICATION FROM BIM MODEL

Each constructability attribute identified in section IV.2 will be linked to the BIM model in the form of a shared parameter. A shared parameter is a parameter that is saved in a universal format with the intention that each design component in the BIM model can have the possibility of acquiring constructability inputs. The purpose of this approach is that when the designer starts to generate his components and develop his design, he/she from day one will add accurate constructability information to the overall BIM model. Only attributes that can be modified from BIM models will be saved in the shared parameter file. These parameters are their input types criteria are:

- Labor availability           Yes/No
- Material availability       Yes/No
- Equipment availability      Yes/No
- Special Skill Labor         Yes/No
- Prefabrication              Yes/No
- Preassembled                Yes/No
Figure IV-6 shows the shared parameters that are added to the Revit software. Shared parameters are saved in a text file (*.txt) so that they can be loaded and used easily by any BIM vendor. Figure IV-7 shows the modified component’s property panel from a snap-shot taken from Revit© 2010 after adding the constructability attributes to the software. Factors found in the dotted area are the added parameters that the user must use to record the constructability input concerning every building component.

Figure IV-6: Shared Parameter File

The output data of these attributes will be part of the constituents of the data model that will be essential for running the model.
IV.3.2  DATA IDENTIFICATION FROM 4D MODEL

As stated earlier, certain constructability factors are of a qualitative nature which makes it exceptionally difficult to quantify their impact on design. For example, many studies have been done on analyzing material access throughout the construction site, and all the contributions included only ideas and knowledge bases to improve proper material accessibility (Koo et al., 2007, Echeverry et al., 1991). There is a little evidence in literature that reported a formal procedure or standard process for material access analysis. In order to analyze qualitative constructability factors, this research argues the idea that visual analysis can be used as basis for studying such qualitative factors if they were properly associated with constructability knowledge. The 4D model developed from linking time durations to design components can be used to study the impact of the design with respect to construction sequence, building envelope, weather, resources accessibility, etc...
Virtual Construction:
- Week 53

Workers / Equipment access to Zone:
- Roof -d

No Workers / Equipment access to Zone:
- R 405
- R 305

Workers / Equipment access to Zone:
- R 205
- R 105

Figure IV-8: Example #1 for a 4D Visual Interpretation
Virtual construction on:
- Week 50

Activity 98: Not Yet Started

Activity 103: 60% Finished

Activity 94: In Progress

Activity 88: Finished

Figure IV-9: Example #2 for a 4D Visual Interpretation

The output of the 4D model can be in the form of either a simulation video or snap-shot pictures captured on a specific pre-planned time period. Figures IV-8 and IV-9 shows two snap-shots examples of a 4D model and how with constructability interpretation can be made using visual analysis. The 10 constructability factors previously incorporated with the 4D model needs 2 main visual aspects to insure proper evaluation:

- Components: The relationship between the time duration and the physical characteristics of the each building component can be very clear in the 4D model and will be used to study the following factors:

<table>
<thead>
<tr>
<th>Construction Sequence</th>
<th>Time Under Ground</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building envelope</td>
<td>Weather effect</td>
</tr>
<tr>
<td>Safety</td>
<td>To adjacent foundation</td>
</tr>
<tr>
<td>To infrastructure</td>
<td></td>
</tr>
</tbody>
</table>
Space Volumes and Paths: By identifying work spaces and worker’s path in the BIM model, as mass volumes and polylines, working space allocations and resource accessibility can be studied from the 4D model. These aspects will be used to study the following factors:

- Material access
- Personnel access
- Equipment access

IV.4 DATA COLLECTION FOR CASE STUDY

In order to develop the BIM model, a building design set had to be collected as a first step. The construction company “Aldo” (www.aldoconstruction.ca) provided the preliminary architectural plans for their new residential project. The project is located in Laval city in Montreal, Canada. A brief project’s description is found in table IV-4.

<table>
<thead>
<tr>
<th>Level</th>
<th>Floor Area (Sq. ft)</th>
<th># of Apartments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basement</td>
<td>6100</td>
<td>0</td>
</tr>
<tr>
<td>First</td>
<td>5065</td>
<td>7</td>
</tr>
<tr>
<td>Second</td>
<td>5920</td>
<td>8</td>
</tr>
<tr>
<td>Third</td>
<td>5920</td>
<td>8</td>
</tr>
<tr>
<td>Fourth</td>
<td>5920</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>28925</td>
<td>31</td>
</tr>
</tbody>
</table>

The provided plans from the construction company were in the form of 2D drawings saved in an Adobe Acrobat© format. Sample of the plans are found in appendices D. Since the received plans were for individual apartments only, complete floor plans for all
levels had to be developed first before generating the BIM model. Other construction details like material selection, installed units or components’ specification were either assumed or gathered from the company’s portfolio.

**IV.5 SUMMARY**

This chapter discussed four points that constitute the data collection process needed to generate and run the model. Factors incorporated in the model were collected from literature. Data gathered from questionnaire surveys helped in assessing the relative weights of these factors. Criteria rationale needed to support the evaluations schemes were also discussed in this chapter along with the data needed to implement and demonstrate the case study. Moreover, the technique proposed to gather constructability information from BIM and 4D models is described in details in this chapter.
Ch V. Constructability Assessment Framework: 
*Development and Implementation*

Assessment of constructability of a particular design requires the development of a model which converts the abstract concept of constructability into quantified values to make it easy to be calculated. This can be done by developing an assessment model and associate it with a generic evaluation scheme. In this chapter, the development and implementation of the constructability assessment framework is explained and discussed in detail. Figure V-1 shows different topics covered in this chapter that explains the steps followed in building and running the assessment model.

![Diagram showing the assessment framework and its components](image)

*Figure V-1: Topics Discussed In Building and the Running the Model*
V.1 BIM Model Development

This research uses a BIM model as a single repository virtual model to store and link construction data along with design components. The following sections explain how BIM models will be used throughout the model development process. The reason behind choosing BIM is based on the benefits of BIM which are discussed in details in section II.3 and this issue will be stressed more here.

V.1.1 Identify Components Specifications

Based on the definition of BIM, data used for executing the construction drawings are linked to their respective design components. The following 3 points will show how building elements’ specification are used and modified as to provide constructability input for the assessment model.

➢ Design attributes: Figure V-2 shows a typical exterior wall with a stone exterior finish. The window associated in this wall is an ellipse shaped one with a fixed glass panel. Assuming that the elliptic window installation needs a specialized skilled labor, stone material is unavailable, equipments to fix the window are unavailable and the wall component is fabricated on-site, Figure V-3 shows how these design and construction information will be transformed to constructability input in the BIM model.
Figure V-2: Wall Example #1

Figure V-3: Constructability Input For Wall Example #1

Figure V-4 shows another example of an exterior wall component with a red brick exterior finish and contains an arched window with two hinged glass panels. Assuming that there is no need for a special skilled labor all the resources are available and the entire wall is a prefabricated panel, Figure V-5 shows how this scenario can be interpreted in the BIM model.
Component’s Flexibility: Flexibility rationales identified in section IV.1.2 are interpreted in Figure V-6. To improve flexibility of designs, designers have to check their building components against flexibility rationale criteria and record the findings in the modified BIM property panel for each design element.
Figure V-6: Flexibility Analysis for a Typical Design Apartment

<table>
<thead>
<tr>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Labor Availability</td>
</tr>
<tr>
<td>Prefabrication</td>
</tr>
<tr>
<td>Equipment Availability</td>
</tr>
<tr>
<td>Flex_Effect of Change</td>
</tr>
<tr>
<td>Flex_Position Flexibility</td>
</tr>
<tr>
<td>Flex_Potential for change</td>
</tr>
<tr>
<td>Flex_Readiness for Change</td>
</tr>
<tr>
<td>Material Availability</td>
</tr>
<tr>
<td>Special Skill Labor</td>
</tr>
<tr>
<td>Standard Dimension</td>
</tr>
</tbody>
</table>

Figure V-7: Flexibility Attribute Values Recorded In BIM Model

As per Figure V-6, the dotted arrows shows that the designated internal walls have a potential for change concerning position, where the arrows with the cross sign found besides the external walls show that there is no potential for change. The arrows with
question marks on the walls dividing the 2 apartments shows that a decision must be made concerning the effect of changing the position of this internal partition on the two nearby spaces. Concerning building materials, each building component can be studied alone to figure out whether there is a potential for material change or not. The sink component in the kitchen can be revolved around its center and thus its position flexibility can be highly achieved. All of these analyses are made by the design team on the BIM model concerning a particular given design and then transferred to constructability input values. Input values can be made for each component alone or per a whole family. For example, all internal partition walls with width= 125 mm and a fire rated protection = 2H can be considered as a single family and can have the same constructability input concerning flexibility. Figure V-7 shows how flexibility attributes’ values can be recorded in BIM model.

V.1.2 CREATING PARAMETRIC RELATIONSHIPS

Parametric relationships between design components mean that they have a logical interconnection relationship between them. This aspect is considered one of the most important features of a BIM model. In other words, if the user changed a particular building component, any linked component to it will be updated automatically, thus preventing rework, reducing modification time and increasing accuracy of the design. The three examples presented here aim to clarify this point from a constructability point of view and explains how BIM models can contribute to improve constructability analysis:
Automatic constructability rules: BIM parametric features can be very helpful in identifying and modifying constructability aspects in a design. Figure V-8 shows a space annotation “Room 3” as a part of different spaces included in a single apartment. Design specification, rules and regulations or any other needed construction data can be linked to this particular space and be used for the constructability analysis. For example, details like finishing material, ceiling height, construction equipment involved, utilities, etc, can be all used in identifying the space characteristics. Constructability input can be added to this given space and used as a basic rule for the given project; thus all spaces with the same name and function will have the same constructability input. The benefit gained from this aspect is that a single data modification for a specific defined space will be automatically applied to all spaces that have the same specification. The same concept can be applied to all kind of spaces; toilets, kitchens, corridors, emergency exists, etc... Figure V-8 shows how constructability input can be attached to a space mass in a BIM model so that its data can be exported to the assessment model.

Figure V-8: Analyzing Constructability Aspect Using BIM Parametric Features
All the construction data of all the design components incorporated in room #3 are saved in the BIM model using the characteristics of “family” and “type”. Any data entry to the defined space “room #3” will be applied automatically to all building components associated in this space.

- Working space allocation: Working spaces like storage areas or fabrication area can be identified in the design phase and linked to their associated design components. Figure V-9 shows how space attributes are saved in the BIM model while Figure V-10 shows a typical fabricated space area located near its designated building element. When the user modifies the original design elements, working space areas will be automatically modified since working space areas are linked parametrically to their components.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction</td>
<td></td>
</tr>
<tr>
<td>Labor Availability</td>
<td></td>
</tr>
<tr>
<td>Prefabrication</td>
<td></td>
</tr>
<tr>
<td>Equipment Availability</td>
<td></td>
</tr>
<tr>
<td>Flex Effect of Change</td>
<td></td>
</tr>
<tr>
<td>Flex Position Flexibility</td>
<td></td>
</tr>
<tr>
<td>Flex Potential for change</td>
<td></td>
</tr>
<tr>
<td>Flex Readiness for Change</td>
<td></td>
</tr>
<tr>
<td>Material Availability</td>
<td></td>
</tr>
<tr>
<td>Special Skill Labor</td>
<td></td>
</tr>
<tr>
<td>Standard Dimension</td>
<td></td>
</tr>
<tr>
<td>Dimensions</td>
<td></td>
</tr>
<tr>
<td>Area</td>
<td>165.755 m²</td>
</tr>
<tr>
<td>Perimeter</td>
<td>17.8302</td>
</tr>
<tr>
<td>Unbounded Height</td>
<td>4.6082</td>
</tr>
<tr>
<td>Width</td>
<td>Not Computed</td>
</tr>
<tr>
<td>Identity Data</td>
<td></td>
</tr>
<tr>
<td>Number</td>
<td>1</td>
</tr>
<tr>
<td>Name</td>
<td>Room</td>
</tr>
<tr>
<td>Comments</td>
<td></td>
</tr>
<tr>
<td>Occupancy</td>
<td></td>
</tr>
<tr>
<td>Department</td>
<td></td>
</tr>
<tr>
<td>Base Finish</td>
<td></td>
</tr>
<tr>
<td>Ceiling Finish</td>
<td></td>
</tr>
<tr>
<td>Wall Finish</td>
<td></td>
</tr>
<tr>
<td>Floor Finish</td>
<td></td>
</tr>
<tr>
<td>Phasing</td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>New Construction</td>
</tr>
</tbody>
</table>

Figure V-9: Space Property Panel
Figure V-10: Working Space Linked To Building Elements

V.2 4D MODEL

As explained in section II.3.5 a 4D model is used to test the effect of time on any given 3D model so that factors like resources accessibility and construction sequence or building envelope can be analyzed. This section will explain the developing process of the 4D model which starts with generating the time schedule sheet and then linking each scheduled activity with its corresponding design component.
V.2.1 Time Schedule Sheet

4D model is defined as the combination of time schedule and a 3D model design. Time schedule will be developed based on the plan which the construction team will use for executing the project. The more the detailed the schedule is, the better the output gained from the 4D model. Each scheduled activity will be linked to its corresponding building component. Any scheduling software could be used. Since the whole constructability assessment is done during early phases of the project, it is not a necessary that the schedule be in its final form.

V.2.2 Generating the 4D Model

When a preliminary schedule is available, a 4D model could be developed using available such as NavisWorks ©. When all planned activities duration are attached to their respective building elements, the 4D model will start to simulate the effect of time on the given design. The simulation is in the form of a video where the user can see the sequence of construction in an animated form. Snap-shots from the model can also be used for the detailed analysis. The visualization output of the 4D model can be adjusted as to meet the specific requirements of the constructability test proposed by the design team. For example, if activities underground are considered a single phase and needs to have a separate constructability feedback, the 4D model can be adjusted to only simulate the underground activities.
V.3 DATA MODEL DEVELOPMENT

In order to calculate the overall constructability score, all the output that are exported from BIM and 4D models used to be properly categorized and assessed. This section explains the process used to categorize the output and develop the data model.

BIM models save each design component’s information with a unique component ID, so that no conflicts can occur when dealing with data exchange. Based on this ID uniqueness feature, all components’ characteristics can be exported from the BIM model and imported to the data model. Microsoft Access© 2007 was used to develop the data model which will be needed for both the assessment model and the user friendly tool. After importing all the building data to the Access© based model, each constructability factor will have a “one to many” relationship with all BIM components that are associated with this particular factor. Thus, when it comes to the assessment of a certain constructability factor, only the needed information will be presented for that factor and not the entire output of the BIM model.

In addition to the unique ID that each design component has, BIM components also have 2 important characteristics: family and type. Family represents the main description of components like wall, door, window, etc... while type represent specific kind of a family component like: internal wall 1 hour fire rated or wooden door single flush panel. The developed data model used these 2 aspects of BIM components to categorize the whole design components. Figure V-11 summarizes this process and gives an example for categorizing the data for factor component flexibility.
Figure V-11: Data Model Development Process
V.4 SMART IMPLEMENTATION

This section explains the technique proposed to evaluate the impact of implementing constructability principles on designs. As previously explained, the abstract concept of constructability makes it difficult to quantify it in any given design. Since constructability has no specific data references which can be used as baselines practices, SMART is used in this research to evaluate this abstract nature. The following three points discuss how SMART application will be used to transform the subjective assessment of the design team into quantified values.

V.4.1 PROPOSED EVALUATION SCHEME

Evaluation schemes are based on both project specific rules and general constructability rules. General constructability rules are gathered from literature and are based on accepted rules by numerous numbers of researches works and construction research institutes. While specific constructability rules are standards that key project stakeholders, especially owners, designers and contractors, decide to use as guide lines to meet specific design requirements. Figure V-12 shows how this scheme is implemented in the assessment model.

After developing the BIM and the 4D model, all the output will be exported to a single data model in the form of general constructability output. In the data model, which is generated using Access© 2007, the general data is categorized and distributed based on the proposed criteria rationale for each factor and as per the data model development process discussed in section V.3. Using Access© application, constructability information will be analyzed using one of two techniques: Quarry or Checklist. Quarries
are based on simple mathematical calculations (sum, average) and are used to simplify the generated quantities from the BIM model. The output of these queries will be used to evaluate constructability attributes based on the project rating criteria that are proposed in sections V.4.2 and V.4.3. Checklist is another method to analyze the output data and they are lists that contain attributes related to only 4 constructability factors. This method is proposed because the rationale behind these factors is based on specific identified points. By identifying the number of checked or unchecked attributes found in the lists the analysis of the corresponding factor can be possible. Thus, by evaluating the results of either the quarries or the checklists, the user will rate the impact of the constructability factor on design using the rating scale and criteria provided for the studied factor. The last step in this process is to transform the ratings into utility values using the unified SMART rating scale.

The example presented here assumes a construction scenario where 67% of needed materials are available. As per this scheme the rating is based on the following 2 points:

- General constructability rule: which states that the more the percentage of available material is, the better the constructability of design.

- Specific constructability rule: the accepted range of material availability is between 60% and 80%.

Thus, the impact of constructability on design of 67% of material availability falls in the Good criteria. The utility value \((U)\) of the factor “material availability” using SMART in this scenario is equal to 0.75. The proposed process for rating is the same for all the factors. Figure V-13 shows an overview of the evaluation process using the presented example.
16 Constructability Factors

6 Factors
- Obtained from BIM
- Export as Components' Data

10 Factors
- Obtained from 4D
- Export as 4D Simulation / Simulation Snapshots

Walls
Resources
Construction Sequence

Design Attributes
Construction Attributes
External Impacts

Queries OR Checklist

Based on Specific Stakeholders' Evaluation Criteria

Rating
SMART
Utility Value

Figure V-12: Detailed Evaluation Process from BIM and 4D Models
Figure V-13: Evaluation Scheme Overview with an Example
V.4.2 PROPOSED RATING CRITERIA FOR BIM MODEL OUTPUT

This section presents the proposed rating criteria (Table V-1) for factors incorporated in the BIM model. Rating criteria will be based on factors’ rationales which are previously discussed in section IV.2. The column “Quarries” stands for the calculations needed to evaluate the overall impact of a particular factor on constructability of designs. Information found under the column “Relation to Constructability Principle “are used as generic principles that can be applied to all building designs.

TABLE V-1: Rating Criteria for Factor Incorporated From BIM Model

<table>
<thead>
<tr>
<th>Constructability Factor</th>
<th>Criteria Rationale</th>
<th>Quarries</th>
<th>Relation to Constructability Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabrication</td>
<td>Prefabricated Components</td>
<td>% of prefabricated components</td>
<td>the HIGHER the % the BETTER the constructability</td>
</tr>
<tr>
<td></td>
<td>Preassembled Components</td>
<td>% of preassembled components</td>
<td>the HIGHER the % the BETTER the constructability</td>
</tr>
<tr>
<td>Grid Layout</td>
<td>Horizontal Grids</td>
<td>N/A</td>
<td>the MORE modular the BETTER the constructability</td>
</tr>
<tr>
<td></td>
<td>Vertical Grids</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Orbital Grids</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Standard Dimensions</td>
<td>Standard Components</td>
<td>% standard components</td>
<td>the HIGHER the % the BETTER the constructability</td>
</tr>
<tr>
<td></td>
<td>Custom-made Components’</td>
<td>% custom-made components</td>
<td>the LOWER the % the BETTER the constructability</td>
</tr>
<tr>
<td>Component Flexibility</td>
<td>Potential for Change</td>
<td>% of components that have potential for change</td>
<td>the HIGHER the % the BETTER the constructability</td>
</tr>
<tr>
<td></td>
<td>Readiness for Change</td>
<td>% of components that are ready for modification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Position Flexibility</td>
<td>% of components that can change position horizontally</td>
<td></td>
</tr>
</tbody>
</table>
V.4.3 Proposed Rating Criteria for 4D Model Output

Similar to the previous section, rating criteria for factors incorporated from the 4D model are proposed in Table V-4. There are 4 factors that need a specific checklist to properly evaluate their impact on constructability and they are also presented in this section. Checklists contain a list of critical aspects that affects a given constructability factor. These checklists will be found automatically in the application tool developed. Based on factor rationale, the two used scales are proposed as per Figure V-14 and their respective utility values readings are found in Table V-2 and Table V-3.

<table>
<thead>
<tr>
<th>Quarry Value (QV)</th>
<th>Rating Criteria</th>
<th>Utility Value (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>If 0% &lt; QV &lt; 20%</td>
<td>Very Bad</td>
<td>U= 0</td>
</tr>
<tr>
<td>If 20% &lt; QV &lt; 40%</td>
<td>Bad</td>
<td>U= 0.25</td>
</tr>
<tr>
<td>If 40% &lt; QV &lt; 60%</td>
<td>Moderate</td>
<td>U= 0.5</td>
</tr>
<tr>
<td>If 60% &lt; QV &lt; 80%</td>
<td>Good</td>
<td>U= 0.75</td>
</tr>
<tr>
<td>If 80% &lt; QV &lt; 100%</td>
<td>Very Good</td>
<td>U= 1</td>
</tr>
</tbody>
</table>
TABLE V-3: Proposed Utility Values for Scale #2

<table>
<thead>
<tr>
<th>Quarry Value (QV)</th>
<th>Rating Criteria</th>
<th>Utility Value (U)</th>
</tr>
</thead>
<tbody>
<tr>
<td>If 0% &lt; QV &lt; 20%</td>
<td>Very Good</td>
<td>U = 1</td>
</tr>
<tr>
<td>If 20% &lt; QV &lt; 40%</td>
<td>Good</td>
<td>U = 0.75</td>
</tr>
<tr>
<td>If 40% &lt; QV &lt; 60%</td>
<td>Moderate</td>
<td>U = 0.5</td>
</tr>
<tr>
<td>If 60% &lt; QV &lt; 80%</td>
<td>Bad</td>
<td>U = 0.25</td>
</tr>
<tr>
<td>If 80% &lt; QV &lt; 100%</td>
<td>Very Bad</td>
<td>U = 0</td>
</tr>
</tbody>
</table>

TABLE V-4: Evaluation Scheme for Factors Incorporated In the 4D Model

<table>
<thead>
<tr>
<th>Factor</th>
<th>Criteria Rationale</th>
<th>Queries</th>
<th>Relation to Constructability Principle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Construction Sequence</td>
<td>Physical relationships among building components</td>
<td></td>
<td>Building components are spatially restricted; weather protected, or gravity supported by other components. Activity sequencing has to respond to these inter component relationships</td>
</tr>
<tr>
<td></td>
<td>Trade interaction</td>
<td>N/A</td>
<td>Activity sequencing has to take into consideration the effect of trade interaction during construction phase</td>
</tr>
<tr>
<td></td>
<td>Path Interference</td>
<td></td>
<td>Building components have to be moved around jobsite in order to be installed. Activity sequence has to guarantee an interference-free path for installation of any component.</td>
</tr>
<tr>
<td></td>
<td>Code Regulation</td>
<td></td>
<td>Activity sequencing is also response to construction-phase safety considerations</td>
</tr>
<tr>
<td>Time Under Ground</td>
<td>Total project Duration</td>
<td>% of days of working activities under ground level</td>
<td>the LOWER the % the BETTER the constructability</td>
</tr>
<tr>
<td></td>
<td># of days of planned activities under ground level</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Parameter Description</td>
<td>Calculation and Interpretation</td>
<td></td>
</tr>
<tr>
<td>----------------------------------</td>
<td>----------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Building Envelope</td>
<td>Total project Duration</td>
<td>% of # of passed days to finish envelope to total project duration. The EARLIER it is completed, the BETTER it is.</td>
<td></td>
</tr>
<tr>
<td></td>
<td># of days passed when envelope works are completed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weather Effect</td>
<td># of days with critical weather</td>
<td>% of days with planned activities on critical weather days. The LOWER the % the BETTER the constructability</td>
<td></td>
</tr>
<tr>
<td></td>
<td># of days which contains planned activities for envelope works on bad weather days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Safety</td>
<td>Ref to Safety checklist</td>
<td>% of checked criteria. The HIGHER the % the BETTER the constructability.</td>
<td></td>
</tr>
<tr>
<td>Material Access</td>
<td>Ref to Material checklist</td>
<td>% of checked criteria. The HIGHER the % the BETTER the constructability.</td>
<td></td>
</tr>
<tr>
<td>Personnel Access</td>
<td>Ref to Personnel checklist</td>
<td>% of checked criteria. The HIGHER the % the BETTER the constructability.</td>
<td></td>
</tr>
<tr>
<td>Equipment Access</td>
<td>Ref to Equipment checklist</td>
<td>% of checked criteria. The HIGHER the % the BETTER the constructability.</td>
<td></td>
</tr>
<tr>
<td>To adjacent Foundation</td>
<td>Apply clash detection using predefined rules</td>
<td>If 1 clash is detected then constructability is Very Bad. If 0 clash detected then constructability is Very Good</td>
<td></td>
</tr>
<tr>
<td>To Infrastructure</td>
<td>Apply clash detection using predefined rules</td>
<td>If 1 clash is detected then constructability is Very Bad. If 0 clash detected then constructability is Very Good</td>
<td></td>
</tr>
</tbody>
</table>
A common finding for resources (material, personnel, and equipment) accessibility factors is that it is not feasible to analyze all resources accessibility aspects in a given project. This research suggests dividing the whole construction phase into sub-phases so that only activities associated on critical paths or complex construction spaces are tested for accessibility issues. Each checklist will be analyzed for each phase and the overall impact will be used to rate the factor.

To start with material access factor, researches’ work does not specify a standard procedure to implement it; however they defined specific rationale to follow. These rationales are recorded and presented in Table V-5 (Riley and Sanvido, 1995) in addition to their proposed analysis criteria. Based on the 4D model simulation, the user has to check or uncheck each check box regarding the proposed areas. In case any identified area is checked as inaccessible area, the whole factor will be rated very bad for that
particular phase. The factor will be rated based on the number of recorded conflicts and as per the proposed rating criteria.

TABLE V-5: Generic Checklist for Material Access Analysis

<table>
<thead>
<tr>
<th>Suggested Areas</th>
<th>Identified Area</th>
<th>Conflict with other Space</th>
<th>Inaccessible Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloading Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Staging Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prefabrication Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Protected Area</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table V-6 provides the checklist for personnel access rating criteria. The rationales are gathered from (Riley and Sanvido, 1995). Any checked conflict will be considered critical as it may compromise the safety of the workers or cause the delay of an activity. The same concept of phase's categorization will be implemented here.

TABLE V-6: Generic Checklist for Personnel Access Analysis

<table>
<thead>
<tr>
<th>Suggested Areas</th>
<th>Identified</th>
<th>Conflict with Workers Path</th>
</tr>
</thead>
<tbody>
<tr>
<td>Debris Path</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hazardous Working Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scaffolding Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stair Cases Access</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table V-7 shows the checklist for equipment access analysis; the data is extracted from the work of Riley and Sanvido (1995). An equipment occupied place is identified as the space occupied by an equipment or a temporary area which is used to support other activity work elements. This checklist can be used to analyze the accessibility for several
equipment spaces. If a critical equipment space (ex. fixed or mobile cranes), is not identified as accessible, the whole factor for that particular phase will be rated as very bad with a utility value =0.

**TABLE V-7: Generic Checklist for Equipment Access Analysis**

<table>
<thead>
<tr>
<th>Suggested Areas</th>
<th>Identified</th>
<th>Conflict with another space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unloading Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Working Area</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment occupied Area</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Similar to the previous checklists, Table V-8 shows the checklist for safety analysis. Data are gathered from (Gambatse et al., 1997). This list can be modified as to meet the different standards for different construction teams and designers.

**TABLE V-8: Generic Checklist for Safety Analysis**

<table>
<thead>
<tr>
<th>Suggestion</th>
<th>Purpose</th>
<th>Revised and checked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indicate on the contract drawings the locations of existing underground utilities and mark a clear zone around the utilities.</td>
<td>To allow proper sloping of excavation</td>
<td></td>
</tr>
<tr>
<td>Design Parapet and window sills to be 42 inch and provide support for guardrails</td>
<td>A parapet of this height will provide immediate guardrail protection and eliminate the need to construct a guardrail during construction or future roof maintenance.</td>
<td></td>
</tr>
<tr>
<td>indicate hazards locations</td>
<td>Maximize precaution</td>
<td></td>
</tr>
<tr>
<td>---------------------------</td>
<td>---------------------</td>
<td></td>
</tr>
<tr>
<td>Design components to be prefabricated or erected on the ground</td>
<td>Reduce worker exposure to falls from elevation and the risk of workers being struck by falling objects.</td>
<td></td>
</tr>
<tr>
<td>Design underground utilities to be placed using trenchless technologies</td>
<td>Eliminate safety hazards associated with trenching especially around roads and pedestrian traffic surfaces</td>
<td></td>
</tr>
<tr>
<td>Position mechanical, piping and electrical controls away from passageways and work areas but still within reach for easy operation</td>
<td>Create safety hazards for construction and maintenance workers</td>
<td></td>
</tr>
<tr>
<td>Do not allow schedules with sustained overtime (maintained at length without interruption or weakening)</td>
<td>Workers will not be alert if overtime is maintained over a sustained period</td>
<td></td>
</tr>
<tr>
<td>Permanent stairways and walkways are designed to be constructed first</td>
<td>to minimize the use of temporary scaffolding</td>
<td></td>
</tr>
<tr>
<td>locate overhead power lines for cranes</td>
<td>reduce contact with hazardous utilities</td>
<td></td>
</tr>
</tbody>
</table>

**V.5 CONSTRUCTABILITY ASSESSMENT MODEL**

The assessment model developed in this section is based on the two decision making techniques AHP and SMART. The first part of this section explains how the model is developed and how it integrates the use of BIM and 4D model to calculate the final score. The second part, explains how the model is used to simulate and automate constructability assessment of designs.

**V.5.1 MAUT CALCULATION AND CONSTRUCTABILITY INTERPRETATION**

The general idea behind developing the assessment model is based on transforming the subjective assessment of constructability knowledge to a quantified value so that it is easy to analyze and improve. From this perspective, the model has to
take into consideration 2 main attributes, the weight of each factor and the utility value of each factor. Constructability index reflects the impact value of a particular factor on the overall constructability score and is calculated using this generic equation:

\[ C_i = W \times U \] \hspace{1cm} (1)

Where:

- \( C_i \) is constructability index
- \( W \) is the relative weight of constructability factor
- \( U \) is the utility value.

\( C_i \) is calculated for each individual factor using equation #1 and the total constructability score is calculated using equation #2

\[ C_t = \sum_{f=1}^{16} W_f \times U_f \] \hspace{1cm} (2)

Where:

- \( C_t \) is total constructability score,
- \( f \) is constructability factor,
- \( W_f \) is the weight of each factor and
- \( U_f \) is the utility value for each factor.

Values for \( W \) and \( U \) values were discussed in detail in sections IV.1.1. Figure V-15 shows a summary of the overall process developed to generate the model where AHP and SMART are integrated to calculate the overall score. All of the processes are automatic except the SMART application where the user has to input manually the rating. The interpretation of the final constructability score will be as follows:
- In case a where single design option is present; the final score reflects the level of impact of constructability principles on this design as per specific stakeholders' criteria. Thus the higher the score, the more the design meets the predefined constructability standards.

- In case of multiple design options, the alternative with the highest score will be considered the best design that meets the constructability demands of a particular design team.

Figure V-15: Integration of AHP and SMART in the Model
The final score does not mean that a particular design alternative is more constructible than the others in a general sense. The score only reflects the level of implementations of constructability principles on the tested design. Since each project is unique and each design team has a unique working methodology, constructability indexes cannot be generic. The aim of the proposed model is to evaluate constructability of building designs in a quantified manner. The scale presented in Figure V-14 is based on the SMART scale used throughout the assessment process and provides tolerances ranges as to accurately evaluate the score.

V.5.2 MODEL SIMULATION AND AUTOMATION

The proposed assessment model can be used to establish more constructible designs by applying necessary modifications to the original design components’ that recorded a bad impact on constructability of designs. The assessment process can be automated until maximum possible constructability score is achieved. Since BIM model is used as the basic virtual data model, each design element that leads to a low constructability index can be reviewed and its specification can be modified as to increase the overall score. As shown in the flowchart illustrated in Figure V-16, the assessment method can be automatic in the sense that any modification done to any design component, the new data can be found automatically in the assessment platform to be evaluated.
Figure V-16: Constructability Assessment Simulation Process

\[ C_t = \sum_{f=1}^{16} W_f \times U_f \]
In addition, any modified schedule sheets or activities’ time duration can be reflected in the 4D model. This process is very beneficial since a design team can test as many alternatives as they want or try many “what if” scenarios to their building proposals until maximum possible constructability score is achieved.

V.6 MODEL IMPLEMENTATION

This section explains how the proposed method is implemented from a project environment point of view. The proposed strategy is generic and can be applied to different types of building projects (residential, industrial, power, etc…) on condition that relative constructability factors have to be identified and weighted to match each particular building type. The two points in this section discusses when and how to implement the proposed method.

V.6.1 CONDITIONS TO RUN THE MODEL

Before implementing constructability assessment on any given design, two constrains must be addressed, namely time and cost. These constrains have to be met before running the model, because if the project is over budget or over time, then constructability analysis is useless. Thus, the user will only run the assessment model if time and cost constrains are met. BIM helps in automatic quantities take off as to have a precise estimation of the designated project. These quantities are used to verify the primary project budget. Similarly 4D models will verify if the project is within agreed time limits. If one of the two constrains is not met, then the whole project has to be modified before studying constructability. Figure V-17 summarizes this condition
statement and shows that budget condition have to be met first since project schedule relies on project quantities to properly estimate activity durations.

![Flowchart](image)

Figure V-17: If Then Condition Process

V.6.2 IMPLEMENTATION STRATEGIES

As per the American Institute of Architects (AIA) guidelines concerning the IPD implementations, the earlier stakeholders are involved in the project, the more overall benefits can be achieved (AIA, 2007). From this perspective, this research argues the
idea that working in an IPD environment can help produce more constructible designs. Figure V-18 shows a detailed description on how to implement the proposed constructability assessment methodology in real life projects. The owner, architect and contractor develop the BIM and the 4D model based on the input of all stakeholders involved in the project. In the case where the contractor has not been selected yet, BIM models when complete can produce enough data for contactors to bid on. These data includes but not limited to: complete design plan sets, bill of quantities, building specification, quality standards, etc...These basic building information can help develop what is called “primary contract” (Khemlani, 2007). When the contract has been awarded, the contractor will then be introduced to the design team and his/her feedback to the design will be included. At this point, both the contractor and the designer will upgrade the design proposal taking into account all the newly addressed concerns. In the traditional project delivery methods, this process is done after the design is completed. After finalizing the design, constructability assessment will be made using the proposed model, and as stated before continuous design modification can be done until maximum constructability score is achieved. When all stakeholders confirm the final version of the design, the contract will be revised accordingly, and this will be the formal binding statement for all stakeholders.
Figure V-18: Constructability Assessment Process in an IPD Environment
V.7 TOOL DEVELOPMENT

V.7.1 INTRODUCTION

A tool was developed to implement the assessment model. This application is based on Microsoft Access© 2007 and thus requires this program in order to run. Access© 2007 was chosen because of the extended size of data tables which is required to handle the data output from the BIM model. In addition, Access© 2007 has the required options, functions and visual aid to run the model and it is widely used by the industry.

V.7.2 ASSESSMENT TOOL DEVELOPMENT

The development process for the data model was discussed in section V.4. This section will explain the application development process to analyze the data found in the data model. Each constructability factor will have a separate interface. The application contains 7 main modules that serve on all interfaces and 4 optional modules that are interchangeable depending on the factor studied. The 7 main modules are:

- **Factor’s list:** The 16 identified constructability factors are contained in 16 different tabs for each one, as the user may easily navigate among them while doing the assessment.

- **General factor’s information:** this module contains the main and the sub-level classification of the factor along with its relative weight and overall ranking with respect to the other factors. This module is needed to show the importance of the factor.
- **Constructability rules**: rules and guidelines that are extracted from literature are respectively attached to each factor as to aid the user in their ratings.

- **Project rating scale**: this scale is based on the rating criteria proposed in this research and its aim is to reflect the satisfaction of the design team toward each individual constructability factor.

- **Constructability rating scale**: this is a unified scale provided for all factors and it is used to convert the user rating into a utility value.

- **Statistical graphs**: these graphs show detailed analysis of the final constructability score.

- **Refresh button**: this button saves the user input made for each factor and generates the computational platform to run the final score.

As for the optional modules, they are as follows:

- **Data from BIM**: quantified constructability data that are extracted from the BIM model are found in this module. For example number of prefabricated components or percentage of flexible design components.

- **4D simulator screen**: 4D animated simulation video or 4D snap-shots are found here.

- **Checklists**: as discussed earlier, certain factors needs a constructability checklist as a base for the assessment method.

- **Report button**: A report button is provided so that the user can have more detailed information about a factor’s data. For example, a report button can provide information for the design components’ whose materials are not available or which components need a special labor skill.
Figure V-19: Application Development Geometry

After identifying the main and the optional modules, Figure V-19 shows how these modules are linked together as to provide the needed function. Each factor tab contains the information needed for a particular factor. This information along with the corresponding constructability rules, can aid the user choosing the appropriate rating. The application automatically converts the ratings into utility values and performs the needed calculations to calculate the final score.
Figure V-20: Overview for the Application Interface without a Checklist

Constructability Assessment Platform

- Prefabrication
- Grid Layout
- Standard Dimensions
- Weather Conditions
- Material Access
- Safety
- Personnel Access
- Equipment Access
- Construction Sequence
- Time Underground
- To Adjacent Foundation
- To Infrastructure

Constructability Factors

- Number of days with potential bad weather conditions that might stop the work: 67
- Number of days which contains planned activities for envelope on bad weather days: 36
- % of days with planned activities on critical weather day: 59%

Main Classification: Construction Attributes
Sub-Level Classification: Installation
Factor Weight: 0.015
Factor Rank: 13 / 16

Project Rating Scale:

Very Bad | Bad | Average | Good | Very Good
------------------
0 | 0.25 | 0.5 | 0.75 | 1

Constructability Rules:

- Designs should facilitate the enclosure of building at the earliest possible stage to avoid moisture and damage because of bad weather.
- Considering possible timing to avoid carrying out structural work, external finishes, etc., during rainy or typhoon seasons for low and high rise buildings.
Figure V-20 shows a snapshot of one of the interfaces of the application without the need of a checklist. All the available data are fixed and cannot be changed unless the original data from the BIM model is modified. The same applies to the factor’s importance details where all the output data is automatically generated from the AHP calculations. Similarly, Figure V-21 shows a snapshot where a checklist is applicable. The next section explains how the model is implemented using the user input.

![Constructability Assessment Platform](image)

**Figure V-21: Overview for Application Interface with a Checklist**

### V.7.3 OVERVIEW FOR RUNNING THE TOOL

The assessment tool is processed using 2 techniques depending on the type of the factor as shown in Figure V-22. If the factor needs checklist identification, the user has to finish all the checklist identifications first so that the application can analyze the inputs. Based on the results of the checklist, the user selects the proper rating from the constructability rating scale. In case the factor’s assessment relies only on BIM data the user can select the appropriate rating directly by analyzing this data output.
Figure V-22: User Input Process

V.8 DEVELOPED METHODOLOGY AND TOOL IMPLEMENTATION TO

CASE STUDY

As a proof of concept, the developed application previously discussed was tested using a case study in order to test its components. The case study is implemented as per the same procedure proposed in this research which is also summarized in Figure V-23. The process starts by collecting the data needed to generate the BIM and 4D models as previously discussed in section IV.4. The Access-based application including the proposed assessment model is used to test a real life construction project located in Montreal (Carterville), Canada. Revit© Architecture 2010 is used to generate the BIM model, while NavisWorks© 2010 is used to simulate the schedule in the 4D model. Only architectural aspects are considered in this case study for simplicity reasons. Any missing
data was assumed including the project rating scale. The following sections explain these steps in detail.

![Flowchart](image)

Figure V-23: Process Followed to Implement the Case Study

V.8.1 BUILDING THE CASE STUDY MODEL

The BIM model is developed based on completed plans and available construction data (material, partition specification, dimensions, etc...). All unavailable data needed to generate the BIM model are assumed. The Revit© software used contains
the modified shared parameters that are explained in section IV.2.1. Since all design components have parametric relationship with each others, sections, elevations and other details are generated automatically as shown in Figure V-24. Additional snap shots for the project are found in Appendix C.2.

Figure V-24: Automatic Generation of Sections and Elevations

Construction data were linked to design components, using the modified properties’ panel developed in this research and shown in Figure V-25. Using the finished BIM model, quantities were automatically generated from the components to test if the project is within project’s budget. Figure V-26 shows a sample snapshot taken from Revit© 2010 concerning wall schedule details. Other details are found in appendix C.1. Based on the completed design drawings and generated bill of quantities, a time schedule sheet was developed using Microsoft© Project 2007. Figure V-27 shows the six main schedule levels proposed for this case study, the detailed schedule is found in Appendix C.2.
Figure V-25: Data Constructability Input

<table>
<thead>
<tr>
<th>Family</th>
<th>Family and Type</th>
<th>Type</th>
<th>Length</th>
<th>Width</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Exterior - Brick on Ml. Brick Clad</td>
<td>Exterior - Brick on Ml. Brick Clad</td>
<td>212.852</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Exterior - Brick on Ml. Stud</td>
<td>Exterior - Brick on Ml. Stud</td>
<td>283.865</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Foundation - 300mm Concrete</td>
<td>Foundation - 300mm Concrete</td>
<td>25.200</td>
<td>0.300</td>
<td>7</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Foundation - 300mm x 1 m 3</td>
<td>Foundation - 300mm x 1 m 3</td>
<td>94.162</td>
<td>0.300</td>
<td>25</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Generic - 90mm Brick</td>
<td>Generic - 90mm Brick</td>
<td>58.711</td>
<td>0.090</td>
<td>23</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Interior - 123mm Partition (1-hr)</td>
<td>Interior - 123mm Partition (1-hr)</td>
<td>1,014.142</td>
<td>0.124</td>
<td>331</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Interior - 135mm Partition (2-hr)</td>
<td>Interior - 135mm Partition (2-hr)</td>
<td>370.152</td>
<td>0.137</td>
<td>115</td>
</tr>
<tr>
<td>Basic Wall</td>
<td>Basic Wall: Retaining - 300mm Concrete</td>
<td>Retaining - 300mm Concrete</td>
<td>219.082</td>
<td>0.300</td>
<td>46</td>
</tr>
<tr>
<td>Curtain Wall</td>
<td>Curtain Wall: Storefront</td>
<td>Storefront</td>
<td>11.282</td>
<td></td>
<td>1</td>
</tr>
</tbody>
</table>

Figure V-26: Automatic Quantities Takeoff
NavisWorks™ 2010 was used to link time schedule durations with BIM model components. Each building component or components are attached to their respective time duration imported from Microsoft Project data base. The software will automatically simulate the construction sequences as per the schedule time sheet. Figure V-28 shows a snapshot of the NavisWorks™ software used to develop the 4D model. The output of the 4D model was in the form of a simulation video where an animated sequence of construction can be seen. Figure V-29 and V-30 shows 2 virtual simulations of the construction activities on week 10 and week 41 respectively. Figure V-31 shows the simulation of work space allocation. The 4D model uses a default color scheme to differentiate between the components. At any given time, the 4D model can reflect the time schedule in a visual manner. Components with solid colors means that they are already executed, while components with highlighted colors means that there is a construction activity in process. At the top left of the simulation screen a detailed date specifies the name of the activity being executed along with the exact time and duration.

Working space allocations which are originally identified in the BIM model are also shown in the 4D model. Different color schemes can be used to differentiate between
them. Four different construction phases were proposed for this design and they will be used throughout this case study.

After finalizing the BIM and 4D models, data were exported to the developed Access© 2007 user friendly tool. This phase is discussed in the following section.

Figure V-28: Snapshot From NavisWorks
Monday 6:00 A.M. 2/2/2009 Day=68 Week=10

Figure V-29: Simulation of Construction Activities on Week 10

Saturday 7:40 A.M. 9/5/2009 Day=283 Week=41

Figure V-30: Simulation of Construction Activities on Week 41
V.8.2 CONSTRUCTABILITY CALCULATION AND RESULTS DISCUSSION

Data extracted from BIM and 4D model are processed in the data model generated for the application and each factor tab displays the corresponding data whether it was a checklist script or quantified values. Detailed assessments of 5 factors out of 16 are presented in this section along with their respective tool interfaces. Rating criteria that governs the assessment are assumed, while in real life scenarios the rating will reflect the project stakeholders’ requirements. Figure V-32 shows the prefabrication assessment interface. The model showed that 49.72 % of the whole building components are prefabricated components. General constructability rules states that the more the prefabricated components are, the more the positive impact on constructability is. Based on the project rating scale for this factor, 49.72 % falls in the average criteria. The
average criteria as per the constructability rating scale is equivalent to a utility value of $U = 0.5$. The weight of this factor $W = 0.302$, thus $C_t = 0.5 \times 0.302 = 0.151$ as per Equation #1. Details for prefabricated and non-prefabricated components are generated using the report button. These reports are used to identify what elements can be modified as to improve the prefabricated components’ percentage and thus improving constructability. The same process is applied for all the other factors. Figure V-33 shows the study done for the factor components’ flexibility. The BIM model identified 76.89% as a flexibility ratio of the design. Three reports are provided for this factor so identify which components had low, medium or high negative impact on the design in case a change in the components’ specification is required. The weather effect factor was studied using the 4D model as shown in Figure V-34. 67 days were assumed to be recorded as extreme bad weather days where a high probability of interruption or delay can affect exterior works activities. The 4D model showed that there are exterior work activities in 26 days out of the 67 days which gives a ratio of 38.8%. This ratio falls in the good rating criteria and gives a utility value of $U = 0.75$. The safety factor was assessed using the constructability checklist as per Figure V-35. Based on the output of the two models, 7 out of 9 identified safety issues were checked which gives a ratio of 77% and thus the safety rating was concluded to be good. The personnel access factor was assessed in the same manner as per Figure V-36. The analysis of 4 construction phases identified the need for 14 different space allocations. The visual simulation of the 4D model showed a conflict in 6 spaces only which gives a ratio of 42.8% and thus the rating of this factor is average.
Figure V-32: Constructability Assessment for Prefabrication Factor

<table>
<thead>
<tr>
<th>Prefabricated Components</th>
<th>49.72%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabricated List:</td>
<td>□</td>
</tr>
<tr>
<td>Non-Prefabricated List:</td>
<td>□</td>
</tr>
</tbody>
</table>

**Design Attributes:**
- Main Classification: 
- Sub-Level Classification: Standardization
- Factor Weight: 0.213
- Factor Rank: 1/10

**Constructability Rating Scale:**
- Very Bad
- Bad
- Average
- Good
- Very Good

**Constructability Rules:**
- By making use of precast components, substantial on-site operations can be used.
- Designers should focus on the economics of proportions and standardization, simplifying the sequence of fixings and giving sufficient details for all elements to fit together as intended.
- Using prefabrication would ultimately facilitate better management.

**Project Rating Scale:**
- Very Bad
- Bad
- Average
- Good
- Very Good

- 0%
- 20%
- 40%
- 60%
- 80%
- 100%
### Constructability Assessment for Component Flexibility Factor

<table>
<thead>
<tr>
<th>Building Envelope</th>
<th>Weather Effect</th>
<th>Safety</th>
<th>Material Access</th>
<th>Personnel Access</th>
<th>Equipment Access</th>
<th>To Adjacent Foundation</th>
<th>To Infrastructure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabrication</td>
<td>Grid Layout</td>
<td>Standard Dim</td>
<td>Component Flexibility</td>
<td>Resource Availability</td>
<td>Labour Skill</td>
<td>Construction Sequence</td>
<td>Time Underground</td>
</tr>
</tbody>
</table>

#### Main Classification
- **Economical Impact**
- **Components' Flexibility**

#### Sub-Level Classification
- **Factor Weight**: 0.081
- **Factor Rank**: 4/16

#### Constructability Rating Scales

```
<table>
<thead>
<tr>
<th>Very Bad</th>
<th>Bad</th>
<th>Average</th>
<th>Good</th>
<th>Very Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>1</td>
</tr>
</tbody>
</table>
```

#### Constructability Rules:
- Adaptable design with interchangeable components provides room for changes to suit different circumstances.
- Flexible components help contractors in selecting the best relative construction method and use of resources.
- Making a design more flexible leads to a reduction in redesign cost and plays a significant role in responding faster to customer feedbacks by allowing quicker updates in the products and achieving higher levels of performance in a short span of time.
### Constructability Assessment for Weather Effect Factor

<table>
<thead>
<tr>
<th>Main Classification</th>
<th>Number of days with potential bad weather conditions that might stop the work</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>97</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sub-Level Classification</th>
<th>Number of days which contains planned activities for envelope on bad weather days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>26</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Project Rating Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Bad</td>
</tr>
<tr>
<td>0</td>
</tr>
</tbody>
</table>

### Constructability Rules:

- Designs should facilitate the enclosure of building at the earliest possible stage to exclude hindrance and damage because of bad weather.

- Considering possible timing to avoid carrying out structural work, external finishes, etc., during rainy or typhoon seasons for low and high rise buildings.
## Figure V-35: Constructability Assessment for Safety Factor

### Main Classification:
- Sub-level Classification:
- Factor Weight: 0.14
- Factor Rank: 14 / 16

### Number of Identified Items: 9
Number of checked items: 7
% of Revised Items: 77%

### Construction Attributes:
- Installation

### Constructability Rules:
- Indicate on the contract drawings the locations of existing underground utilities and mark a clear zone around the utilities.
- Design parapet and window sills to be 42 inches and provide support for guardrails.
- Indicate hazards locations.
- Design components to be prefabricated or erected on the ground.
- Design underground utilities to be placed using trenchless technologies.
- Position mechanical, piping and electrical controls away from passageways and work areas but still within reach for easy operation.
- Permanent stairways and walkways are designed to be constructed first.
- Locate overhead power lines for cranes.
- Do not allow schedules with sustained overtime (maintained at length without interruption or weakening).

### Project Rating Scale:
- Very Bad
- Bad
- Average
- Good
- Very Good

### Constructability Rating Scale:
- 0
- 0.25
- 0.5
- 0.75
- 1

### Time Under Ground:
- To Adjacent Foundation
- To Infrastructure

### Other Table:
- Prefabrication
- Grid Layout
- Standard Dimensions
- Component Flexibility
- Resource Availability
- Labour Skill
- Construction Sequence
- Material Access
- Personnel Access
- Equipment Access

### Constructability Assessment

#### Rating Scales

**Project Rating Scales**

<table>
<thead>
<tr>
<th>Very Good</th>
<th>Good</th>
<th>Average</th>
<th>Bad</th>
<th>Very Bad</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>80%</td>
<td>60%</td>
<td>40%</td>
<td>20%</td>
</tr>
</tbody>
</table>

**Constructability Rating Scale**

<table>
<thead>
<tr>
<th>Very Bad</th>
<th>Bad</th>
<th>Average</th>
<th>Good</th>
<th>Very Good</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
<td>1</td>
</tr>
</tbody>
</table>

#### Main Classification

<table>
<thead>
<tr>
<th>Sub-Level Classifications</th>
<th>Construction Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources Accessibility</td>
<td></td>
</tr>
</tbody>
</table>

#### Factor Analysis

- **Factor Weight:** 0.022
- **Factor Rank:** 11/10
- **Identified Areas:** 14/20
- **Conflict Areas:** 6/14 (42.8%)

#### Constructability Check List

- **Phase #1**
  - Debris Path
  - Hazardous Working Area
  - Working Area
  - Scaffolding Area
  - Stair Cases Access

- **Phase #2**
  - Debris Path
  - Hazardous Working Area
  - Working Area
  - Scaffolding Area
  - Stair Cases Access

- **Phase #3**
  - Debris Path
  - Hazardous Working Area
  - Working Area
  - Scaffolding Area
  - Stair Cases Access

- **Phase #4**
  - Debris Path
  - Hazardous Working Area
  - Working Area
  - Scaffolding Area
  - Stair Cases Access

- **Identified**
  - Conflict with workers' path

---

**Figure V-36: Constructability Assessment for Personnel Access Factor**
## Constructibility Report

<table>
<thead>
<tr>
<th>Constructibility Factor</th>
<th>Utility Value</th>
<th>Factor Weight</th>
<th>Constructibility Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabrication:</td>
<td>0.50</td>
<td>0.302</td>
<td>0.1510</td>
</tr>
<tr>
<td>Grid Layout:</td>
<td>1.00</td>
<td>0.148</td>
<td>0.1480</td>
</tr>
<tr>
<td>Standard Dim:</td>
<td>1.00</td>
<td>0.075</td>
<td>0.0750</td>
</tr>
<tr>
<td>Components Flexibility:</td>
<td>0.75</td>
<td>0.086</td>
<td>0.0645</td>
</tr>
<tr>
<td>Resources Availability:</td>
<td>1.00</td>
<td>0.025</td>
<td>0.0250</td>
</tr>
<tr>
<td>Labour Skills:</td>
<td>0.25</td>
<td>0.031</td>
<td>0.0078</td>
</tr>
<tr>
<td>Construction Sequence:</td>
<td>0.75</td>
<td>0.048</td>
<td>0.0360</td>
</tr>
<tr>
<td>Time Underground:</td>
<td>0.25</td>
<td>0.008</td>
<td>0.0020</td>
</tr>
<tr>
<td>Building Envelope:</td>
<td>1.00</td>
<td>0.011</td>
<td>0.0110</td>
</tr>
<tr>
<td>Weather Effect:</td>
<td>0.75</td>
<td>0.014</td>
<td>0.0105</td>
</tr>
<tr>
<td>Safety:</td>
<td>0.75</td>
<td>0.012</td>
<td>0.0090</td>
</tr>
<tr>
<td>Material Access:</td>
<td>0.75</td>
<td>0.053</td>
<td>0.0398</td>
</tr>
<tr>
<td>Personnel Access:</td>
<td>0.50</td>
<td>0.019</td>
<td>0.0095</td>
</tr>
<tr>
<td>Equipment Access:</td>
<td>0.25</td>
<td>0.016</td>
<td>0.0040</td>
</tr>
<tr>
<td>To Adjacent Foundation:</td>
<td>1.00</td>
<td>0.110</td>
<td>0.1100</td>
</tr>
<tr>
<td>To Infrastructure:</td>
<td>1.00</td>
<td>0.043</td>
<td>0.0430</td>
</tr>
</tbody>
</table>

**Constructibility Score:**

0.7460

---

![Constructibility Score](image)

**Figure V-37: Constructability Score for 1st Design Alternative**

These assessments were done for the first proposed design alternative and the constructability score which is found in Figure V-37 showed an overall score of 0.740 out of 1 which is evaluated as good based on the scale provided with the report. This scale uses the same ratings as the SMART scale. The interpretation of the final score is based on the constructability requirements proposed for this design and thus this design rated
good. The next figure shows more detailed analysis of the score and the generated graphs helped in identifying which factors and components have to be modified in order to improve the result.

![Pie chart showing the percentage of each factor's contribution to the overall score.]

Figure V-38: Percentage of Each Factor's Contribution to Overall Score

The graph presented in Figure V-38 shows how each factor contributed to the overall calculated score. These calculations are based on the ratio of each index to the score. For example: $C_i$ for prefabrication = 0.1510, and the overall score = 0.7460, thus the percentage of contribution = 20.24%. The aim of this analysis is to clarify how the importance of each factor is reflected on overall constructability of the design.
Start

Phase #1
Calculate Constructability Score

Phase #2
Identify factors with negative constructability issues

Phase #3
Assign conditions for factors modifications

Phase #4
Prioritize the factors

Phase #5
Modify the selected factors

Phase #6
Reassess constructability

NO
Constructability Assessment accepted?

YES
Finish

Explanation
Using the proposed assessment model

Ex: factors that have implementation percentage between 0 and 50%

Based on condition statement first then on factor weight

Based on constructability rules assigned to these designated factors

Using the proposed assessment model

Figure V-39: Design Modification Process
Improving constructability of design in hand starts after the 1st assessment, where the impact on constructability is quantified for each factor. Figure V-39 shows the process proposed to modify the design components based on the analysis achieved from the 1st assessment. The following graphs were generated and studied in accordance with the presented modification process.

![Constructability Factors](image)

**Figure V-40**: Comparison between Factors' Weight and Factors' Index

The modification process starts by studying the indexes achieved from the 1st assessment in order to analyze each factor alone. The developed tool can publish some statistical graphs to assist in this issue. Figure V-40 shows a comparison between factors' weight
values and their corresponding constructability values' index. In an ideal situation, constructability index will be equal to its weight value if the agreed on constructability rules are 100% implemented. The difference between the index value and the weight value indicate that some constructability problems exist. Factors like grid layout or standard dimensions showed maximum constructability compliance with the tested design, while factors like prefabrication and safety showed incomplete conformity with the constructability rules assigned to them. In other words, all factors that have percentage of conformity less that 100% are factors that have negative impact on constructability of designs.

![Constructability Factors Bar Chart]

**Figure V-41: Factors' Order Based On Constructability Conformity**

After identifying which factors have constructability issues to be addressed, the application sorted all the 16 factors by ascending order from lowest to highest
constructability implementation as per Figure V-41. Factors with a 25% implementation percentage means that nearly quarter of the constructability principles designated for these factors were applied. This analysis aims to identify which factors or set of factors have to be addressed first. For this particular case study, the criteria assigned for factor selection is that only factors with percentage of implementation that ranges from 0% to 50% are chosen for improvements. The other factors are accepted as they are because they fall in the criteria decided on. In order to know which factor to starts with, a more detailed graph for prioritizing the selected factors is generated and found in Figure V-42. The priority list is based on the percentage of implementation first then on the weight of the factor. From this perspective, the fabrication factor was the first factor on the list since it has the maximum weight among the selected 5 factors that had an implementation percentage between 0% and 50%.

![Graph showing the factors and their weights](image)

Figure V-42: Priority of Factors to Be Addressed
After identifying which factors have to be restudied and in which order, the modification phase starts. Since each design component has a unique ID code, generated reports were used to identify which components had a negative impact on constructability. For instance, the sample report found in Figure V-43 indicates that the building component with ID= 298132 is not a prefabricated window item since it had a zero value. Thus, this ID was visualized in the BIM model and the decision was made to change it to a prefabricated component. This is the procedure used to for all components associated in the BIM model. As for factors incorporated from 4D model, each reported space or schedule conflict was rechecked and modified. Also, working areas that showed conflicts of spaces are designed.

<table>
<thead>
<tr>
<th>Id</th>
<th>FamilyName</th>
<th>TypeName</th>
<th>Width</th>
<th>Height</th>
<th>T_Prefabricated</th>
</tr>
</thead>
<tbody>
<tr>
<td>53700</td>
<td>M_Fixed</td>
<td>0406 x 0610mm</td>
<td>0.406</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>53702</td>
<td>M_Fixed</td>
<td>0406 x 1220mm</td>
<td>0.406</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>53704</td>
<td>M_Fixed</td>
<td>0610 x 0610mm</td>
<td>0.61</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>53706</td>
<td>M_Fixed</td>
<td>0610 x 1220mm</td>
<td>0.61</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>53708</td>
<td>M_Fixed</td>
<td>0915 x 0610mm</td>
<td>0.915</td>
<td>0.61</td>
<td></td>
</tr>
<tr>
<td>53710</td>
<td>M_Fixed</td>
<td>0915 x 1220mm</td>
<td>0.915</td>
<td>1.22</td>
<td></td>
</tr>
<tr>
<td>53712</td>
<td>M_Fixed</td>
<td>0406 x 1830mm</td>
<td>0.406</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>53714</td>
<td>M_Fixed</td>
<td>0610 x 1830mm</td>
<td>0.61</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>53716</td>
<td>M_Fixed</td>
<td>0915 x 1830mm</td>
<td>0.915</td>
<td>1.83</td>
<td></td>
</tr>
<tr>
<td>182055</td>
<td>M_Archtop with Trim</td>
<td>0610 x 0610mm</td>
<td>0.61</td>
<td>0.61</td>
<td>Non prefabricated component</td>
</tr>
<tr>
<td>182057</td>
<td>M_Archtop with Trim</td>
<td>1220 x 1525mm</td>
<td>1.22</td>
<td>1.525</td>
<td></td>
</tr>
<tr>
<td>182059</td>
<td>M_Archtop with Trim</td>
<td>0610 x 1525mm</td>
<td>0.61</td>
<td>1.525</td>
<td></td>
</tr>
<tr>
<td>182061</td>
<td>M_Archtop with Trim</td>
<td>1830 x 2438mm</td>
<td>1.83</td>
<td>2.438</td>
<td></td>
</tr>
<tr>
<td>182063</td>
<td>M_Archtop with Trim</td>
<td>1830 x 1525mm</td>
<td>1.83</td>
<td>1.525</td>
<td>1</td>
</tr>
<tr>
<td>182065</td>
<td>M_Archtop with Trim</td>
<td>1220 x 2438mm</td>
<td>1.22</td>
<td>2.438</td>
<td>1</td>
</tr>
<tr>
<td>298130</td>
<td>M_Ellipse with Trim</td>
<td>big ellipse</td>
<td>0.915</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>298132</td>
<td>M_Ellipse with Trim</td>
<td>750 x 1500mm</td>
<td>0.75</td>
<td>1.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure V-43: A Sample Report for Prefabricated Components

Modifications were done for all 5 factors either by changing components’ specification in the BIM model or by adjusting the time schedule to solve space conflicts. Certain issues
were mitigated and others were left as they were originally designed. The unchangeable
conflicts are considered as acceptable risks and they will be recorded in the
constructability issue log. These unsolved problems will be reviewed continuously during
the construction phase either through progressive constructability improvements or
continuous attention.

Summary of changes done for this case study are as follows:

➤ Prefabrication: 7.08 % of non prefabricated components were changed to
prefabricated ones.

➤ Labor skill Availability: 28.31% of the building components were modified so
that their specification will not require a special skill labor.

➤ Personnel Access: the 4 predefined phases were revised and only 1 space conflict
was solved.

➤ Equipment access: 2 space allocation conflicts were resolved out of 7 recorded
ones.

➤ Time underground: the assessment showed that out of 399 days (project duration)
95 days had activities executed below ground level, which gives a ratio of 23.8%
and is considered bad. This ratio could not be improved upon revising the original
schedule.

When all possible changes are done, the 2nd constructability assessment starts and new
indexes were automatically calculated after importing the new modified data to the
developed application. Summary for the new results and indexes are presented in Table
V-9 and shown in Figure V-44.
TABLE V-9: Modified Index List for 1st Design Alternative

<table>
<thead>
<tr>
<th></th>
<th>Previous Value</th>
<th>New Value</th>
<th>Previous Index</th>
<th>New Index</th>
<th>Index Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabricated</td>
<td>49.72</td>
<td>56.8</td>
<td>0.1510</td>
<td>0.1510</td>
<td>0.00%</td>
</tr>
<tr>
<td>Labor skill</td>
<td>24.49</td>
<td>52.8</td>
<td>0.0078</td>
<td>0.0151</td>
<td>93.5%</td>
</tr>
<tr>
<td>Personnel Access</td>
<td>42.8</td>
<td>35.7</td>
<td>0.0095</td>
<td>0.0143</td>
<td>50.00%</td>
</tr>
<tr>
<td>Equipment Access</td>
<td>63.6</td>
<td>45.5</td>
<td>0.004</td>
<td>0.008</td>
<td>100.00%</td>
</tr>
<tr>
<td>Time under ground</td>
<td>23.8</td>
<td>23.8</td>
<td>0.002</td>
<td>0.002</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

Figure V-44: Comparison between New Index Values and Previous Ones

Figure V-45: Index Improvement after 1st Modification
Prefabrication and time underground factors showed no constructability index improvement because the improvement done to their corresponding design component was not enough to change the overall rating of the designated factor as shown in Figure V-45. Only reports like the one presented in Table V-1 shows the detailed improvements to each factor. Figure V-46 shows the new constructability assessment report after the 1st modification. In comparison with the first constructability score (0.7460) the new score was 0.7625 with a slight improvement of 2.16%. This procedure can be repeated until no more improvement is made or maximum constructability score is achieved.

**Constructibility Report**

<table>
<thead>
<tr>
<th>Constructibility Factor</th>
<th>Utility Value</th>
<th>Factor Weight</th>
<th>Constructibility Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prefabrication:</td>
<td>0.50</td>
<td>0.302</td>
<td>0.1510</td>
</tr>
<tr>
<td>Grid Layout:</td>
<td>1.00</td>
<td>0.148</td>
<td>0.1480</td>
</tr>
<tr>
<td>Standard Dim:</td>
<td>1.00</td>
<td>0.075</td>
<td>0.0750</td>
</tr>
<tr>
<td>Components Flexibility:</td>
<td>0.75</td>
<td>0.085</td>
<td>0.0645</td>
</tr>
<tr>
<td>Resources Availability:</td>
<td>1.00</td>
<td>0.025</td>
<td>0.0250</td>
</tr>
<tr>
<td>Labour Skills:</td>
<td>0.50</td>
<td>0.031</td>
<td>0.0155</td>
</tr>
<tr>
<td>Construction Sequence:</td>
<td>0.75</td>
<td>0.048</td>
<td>0.0360</td>
</tr>
<tr>
<td>Time Underground:</td>
<td>0.25</td>
<td>0.008</td>
<td>0.0020</td>
</tr>
<tr>
<td>Building Envelope:</td>
<td>1.00</td>
<td>0.011</td>
<td>0.0110</td>
</tr>
<tr>
<td>Weather Effect:</td>
<td>0.75</td>
<td>0.014</td>
<td>0.0105</td>
</tr>
<tr>
<td>Salty:</td>
<td>0.75</td>
<td>0.012</td>
<td>0.0090</td>
</tr>
<tr>
<td>Material Access:</td>
<td>0.75</td>
<td>0.053</td>
<td>0.0358</td>
</tr>
<tr>
<td>Personnel Access:</td>
<td>0.75</td>
<td>0.019</td>
<td>0.0143</td>
</tr>
<tr>
<td>Equipment Access:</td>
<td>0.50</td>
<td>0.016</td>
<td>0.0080</td>
</tr>
<tr>
<td>To Adjacent Foundation:</td>
<td>1.00</td>
<td>0.110</td>
<td>0.1100</td>
</tr>
<tr>
<td>To Infrastructure:</td>
<td>1.00</td>
<td>0.043</td>
<td>0.0430</td>
</tr>
<tr>
<td><strong>Constructibility Score:</strong></td>
<td></td>
<td></td>
<td><strong>0.7625</strong></td>
</tr>
</tbody>
</table>

![Figure V-46: Constructability Final Score for 2nd Design Alternative](image-url)

Figure V-46: Constructability Final Score for 2nd Design Alternative
V.8.3 VALIDATION OF THE PROPOSED MODEL

The question of how to validate an information system design method is a problematic issue. There are inherent problems in evaluating any methodology or design technique since typically no theory, no hypotheses, no experimental design and no data analysis to which traditional evaluation criteria can be applied (Weber, 1997). According to (Rescher, 1977), human knowledge consists of two types:

- **Theses** or “knowledge that”: these define statements or assertions about the world.
- **Methods** or “knowledge how”: these define ways of doing things.

“Knowledge that” or propositional knowledge has been the primary focus of scientific research, which is generally about establishing the truth of particular propositions (hypotheses). The reason is that methods have no truth value; only a practical value. This means that a method does not describe any external reality, since it cannot be true or false, only effective or ineffective (Rescher, 1977). The validity of a method can only be established by applicative success in practice. The objective of validation should not be to demonstrate that the method is “correct” but that it has a rational practice to adopt the method based on its practical success. Pragmatic or practical success is defined as “the efficiency and effectiveness with which a method achieves its objectives” (Moody, 2003). Task performance can be improved in two ways:

- Efficiency improvement: by reducing effort required to complete the task
- Effectiveness: improving the quality of the result.

Based on the previous literature, this research adopted the theoretical model developed by Moody (2003) for validating information systems design methods. The main attributes of the model are:
- **Actual Efficiency**: the effort required to apply a method.

- **Actual Effectiveness**: the degree to which a method achieves its objectives.

- **Perceived Ease of Use**: Is the degree to which a person believes that using a particular method would be free of effort.

- **Perceived Usefulness**: Is the degree to which a person believes that a particular method will be effective in achieving its intended objectives.

- **Intention to Use**: the extent to which a person intends to use a particular method.

- **Actual Usage**: the extent to which a method is used in practice.

![Method Evaluation Model](image)

Figure V-47: Method Evaluation Model (Moody, 2003)

This model was implemented throughout a questionnaire survey send to a design consulting company in the United States named “Faithful & Gould” a member of the ATKINS Group. This company was selected since they have a wide practical experience in constructability analysis and they had been implementing BIM and 4D models in their decision making. Faithful and Gould showed interest with subject and they were presented with more details concerning the approach, objective and benefits of the presented methodology. They were given a 6 point questionnaire (Figure V-48) sheet as
to record their feedback concerning the practicality of the developed methodology from an experienced point of view. This approach of validation was chosen for this research for 2 main reasons:

- The absence of a formal constructability assessment model where the assessment of the proposed model can be compared to.
- The absence of a generic constructability scoring system to validate the scores of new model.

From this perspective, the responses gathered from the experienced firm will give a general overview on how the industry will react toward the new constructability assessment platform. Design methodologies can be validated from an efficient or effectiveness point of views Moody (2003). The limitation of such a validation technique is that a single feedback is not enough to validate whether it proposed model is effective or not.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Scale</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low</td>
<td>Medium</td>
</tr>
<tr>
<td>Actual Efficiency</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Actual Effectiveness</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Perceived Ease of Use</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Perceived Usefulness</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Intention of Use</td>
<td>☐</td>
<td>☐</td>
</tr>
<tr>
<td>Actual Usage</td>
<td>☐</td>
<td>☐</td>
</tr>
</tbody>
</table>

Figure V-48: Questionnaire Form for Methodology Validation
The responses gathered from the “Faithful & Gould” are presented in Figure V-49, where High = 3, Medium = 2 and Low = 1. As per the previous results and the feedback recorded from a personnel interview with the chosen design firm, the integration of BIM technology along with 4D models has a potential to improve constructability assessment of design. Moreover the proposed MAUT approach to quantify the implantation of constructability principles in any given design makes the model easy and flexible to implement.

V.8.4 Sensitivity Analysis

A sensitivity analysis was applied to the generated constructability assessment report as to study how the variation of factors’ weights can affect the overall output of the model. Since the calculation of factors’ weights were based on Canadian experts’ feedback only, the analysis was done to test what is the effect on the overall constructability score if these weights change from one environment to another. The approach used to apply the sensitivity analysis is detailed in Figure V-50. The analysis is done only for the 5 factor’s which carry the highest weight. For each of these 5 factors, a variance from -30% to +30% are applied to each weight and the process found in Figure
V-50 was done for each calculated weight variance. When the modified weight values are calculated, new constructability scores are generated separately based on the proposed model in order to evaluate the effect of the weight variance change on the score. Thus for each of the 5 selected factors, 6 new scores are calculated in addition to the original score as per their corresponding weight variance. A total of 35 scores were generated and plotted as shown in Figure V-51. Each line in the graph represents the percentage of weight variance and the respective new constructability score. Based on this graph the factor “component flexibility” was found to be the less sensitive, which means that in case the weight value of this factor changed within the limits of -30% and +30%, the effect on overall score will be negligible. On the other hand, the factor “prefabrication” was found to be very sensitive; since it holds the highest relative weight; thus any change in its weight’s value will have a recognizable effect on the constructability result.

![Diagram](image)

\[ Ct = \sum_{f=1}^{16} Wf * Uf \]

Figure V-50: Approach Used For the Sensitivity Analysis
V.9 SUMMARY

This chapter explained the process and the rationale behind developing the constructability assessment platform. 16 factors were identified from literature and published journal papers. Survey questionnaires were done throughout Canadian provinces and based on AHP technique; the relative weight of importance of each of the 16 factors was calculated. Prefabrication factor was found to have the highest impact of constructability of designs while construction time underground had the least impact. SMART rating technique was used to assess the design attributes and transform subjective assessment into quantified utility values. Constructability index of each factor was calculated by multiplying the weight of the factor by its corresponding utility value. The final constructability score is found to be the sum of all indexes. Evaluation criteria
based on factors’ rationales were proposed as guidelines and rules for constructability assessment. As a proof of concept, a user friendly tool to assess constructability was proposed and a case study was implemented. The detailed analysis of the calculated indexes can be used to identify constructability negative impacts. The validation results showed that the proposed constructability assessment platform can be used to evaluate constructability implementation in a quantified manner. Moreover the developed platform proved to be flexible enough as it can record automatically any improvement done to the design.
VI.1 RESEARCH SUMMARY

This work has presented a methodology that addresses the challenge faced by construction stakeholders concerning constructability improvement of projects. It offers a platform to assess constructability of building designs. The assessment model considers many design relevant factors, which can be divided broadly into 3 main categories: design, construction and impact on site attributes. Based on 8 constructability principles, 16 design factors were incorporated in the model (qualitative and quantitative factors). In addition to the assessment model, a new platform to improve constructability of design is proposed. This method relies on the use of advanced technology tools used in the construction field like building information model (BIM) and 4D (3D plus time) models. BIM model was used to link and manipulate construction data with 3D components. 4D model was also used to study the effect of time on design proposals.

Constructability calculation is based on two techniques, analytical hierarchy process (AHP) and simple multi attribute rating technique (SMART). AHP was used to relatively weight the factors incorporated in the model based on a survey questionnaire done throughout different Canadian provinces. SMART application is used to transform the rating performance of each constructability factor into a utility value according to the following criteria: very bad = 0, bad= 0.25, moderate = 0.5, good= 0.75, very good = 1.

The proposed assessment methodology combines the use of the 2 previous mentioned decision making techniques with BIM and 4D models in an integrated project delivery
(IPD) approach. This approach can coordinate the work of designers and contractors together at early stages of the project to improve communication and reduce prospective conflicts.

Based on the developed assessment model and the proposed implementation method, an Access©-based tool is developed to assess and evaluate constructability of designs. Owners, designers and contractors can used the developed application to improve the constructability of proposed building designs and thus reduce overall time and cost consumption during construction phases. The developed platform can quantify the impact of constructability on design and identify which design factors needs improvements and thus construction stakeholders can use it to improve the quality of their design proposals.

VI.2 CONTRIBUTION TO KNOWLEDGE

The differences between constructible and less constructible designs are consequently not easily distinguished. By increasing the clarification of constructability concepts; a quantification system to derive comparable scorings representing constructability levels of different designs would be possible and beneficial to all A/E/C users. The proposed platform transformed objective evaluation of constructability reviews done by project team, mainly designers and contractors, into measurable values that are easy to analyze. It also enables designers to self-check and prioritize their efforts for constructability improvements with reference to the constituent scores for various aspects of a design.
The developed platform addressed the problem of assessing the abstract nature of constructability principles in any given object oriented. It contributes to the field of construction management by achieving the following:

- A new assessment model to calculate constructability of designs.
- A new technique to check for constructability implementation in designs that helps owners, designers and contractors integrate their ideas based on state of the art advancement in the construction industry.
- An automated tool that helps project stakeholders evaluates many design alternatives to achieve maximum possible constructible projects in a quantified manner.
- Broaden the usage of objected oriented models as to follow up with the state of the art BIM evolution in the construction industry and promotes the integration between BIM and 4D models tools for the purpose of constructability analysis.

### VI.3 PROPOSED METHOD VS. PREVIOUS WORKS

Table VI-1 shows a brief comparison between previous assessment methods and the one proposed in this research. Integrating 4D and BIM model to assess constructability along with the developed platform had shown a good improvement in the field of constructability assessment. Details for limitation on previous works can found in section II.6.2. This comparison highlights on the benefits of the proposed platform.
concerning problem solving of certain limitations recorded from previous constructability assessment methods.

**TABLE VI-1: Proposed Framework vs. Previous Studies**

<table>
<thead>
<tr>
<th>Previous work on assessing constructability of design</th>
<th>Previous Assessment limitation</th>
<th>Proposed Constructability Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>Buildable Design Appraisal System (BCA, 2005) &amp; Empirical System for Scoring Constructability (Wong, 2007)</td>
<td>Dependant on governmental benchmarks to calculate and evaluate final score</td>
<td>Final score is rated based on project stakeholders’ particular project standards</td>
</tr>
<tr>
<td></td>
<td>Time factor is not included</td>
<td>Time factor is included and assessed using a 4D model</td>
</tr>
<tr>
<td>Constructability Assessment Framework (Zin et al., 2004)</td>
<td>Time factor is not included</td>
<td>Time factor is included and assessed using a 4D model</td>
</tr>
<tr>
<td></td>
<td>All factors are independent from each other and no formal criteria is presented to evaluate the whole design as a single result</td>
<td>All factors are incorporated in a single BIM model with parametric relations. Constructability score is calculated using a well identified platform.</td>
</tr>
<tr>
<td>Cognitive Models for Constructability Assessment (Ugwa et al., 2004)</td>
<td>The whole system is based on knowledge mining protocol and not on design components. It deals with tasks rather than objects.</td>
<td>Assessment model is based solely on design components and stakeholders standards which makes it easier and more practical for designers.</td>
</tr>
<tr>
<td>Fuzzy Quality Function Deployment System (Yang et al., 2003)</td>
<td>Very complex modeling system</td>
<td>Simple calculation procedure with a friendly application and flexible rating criteria.</td>
</tr>
<tr>
<td></td>
<td>Demanding assessment measure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>It needs a lot of input rules</td>
<td></td>
</tr>
</tbody>
</table>

**VI.4 RESEARCH BENEFITS**
This research offers a new model to assess constructability in design and a new platform to implement its principles. During the course of the research, many benefits can be noticed such as:

- It helps in quantifying the abstract nature of constructability so that its evaluation can be easier and more practical.

- The model relies completely on design components; this means that designers can address constructability inputs directly to their proposed building components.

- The use of BIM as a single virtual data repository to integrate and control construction data, helps in improving communication, precision and clearness of project details among all stakeholders.

- 4D models helped in improving schedule visualization and early detection of conflicts concerning construction sequence, work space allocation and resources accessibility.

- The new model is based on simple calculations and a clear implementation strategy which tends to encourage designers and owners to implement constructability more to their projects.

- The use of flexible evaluation criteria which is independent of governmental benchmarks makes the model more generic to meet different construction teams as each one has a different construction working methodology.

- Automatic simulation aspects of the platform help the project team to evaluate and rehearse many designs and construction alternatives easily.
• Construction experience and lessons learned can be recorded and added to the model in the form of constructability rules so that junior designers can use and improve in the future.

VI.5 CONCLUSIONS

The presented research work leads to the development of a constructability assessment model that can transform the abstract concept of constructability knowledge into a quantified value to facilitate analysis and evaluation of designs. Many points can be concluded from the research such as:

• SMART technique is recommended to evaluate theoretical knowledge topics like constructability when clear quantified data is unavailable or when evaluations schemes are based on subjective reasoning.

• From the collected questionnaire, it can be deduced that prefabrication of building components has the highest effect on constructability of designs, while construction time underground has the least effect.

• The more data is collected about attributes and factors affecting constructability the more the AHP results accuracy is. However it is not advisable to collect data for all factors, only for selected ones that meet the requirements of a particular project.

VI.6 LIMITATIONS

VI.6.1 MODEL LIMITATIONS
The developed model integrated the use of AHP and SMART techniques with BIM and 4D models to calculate the constructability impact on designs. There are some limitations inherent in the model such as:

- The number of collected questionnaires is fifteen. The model accuracy can be improved by increasing the number of experts involved in assessing the importance of constructability factors.
- The model assumes that the attributes incorporated in the factors are of equal weight. A more detailed weight distribution can lead to more precise results.
- The model uses only 16 constructability factors that contribute to constructability assessment of designs. Environmental design aspects are not included.
- The proposed assessment platform gives recommendations on what factors needs to be adjusted to improve constructability but does not indicate how.
- The overall constructability evaluation cannot be relied solely on the final score, constructability indexes along with generated reports have to be taken into consideration.

VI.6.2 Tool Limitations

An Access-based application was built based on the developed model which uses the results of AHP and SMART to assess the output of BIM and 4D models. However, there are some limitations in using this application:

- Even though the application is flexible concerning choosing the best evaluation among the predefined 16 factor, other factors may be needed for a particular project, which are not considered in this model.
• Due to technical constrains (computer programming resources), only input from BIM models to Access data model are done.

• The developed tool is based on Ms Access© version 2007, and thus it requires this software to operate and function it.

VI.7 RECOMMENDATIONS AND FUTURE WORK

Some of the recommendation and future works that can enhance the model and the research in general are listed below.

• More factors can be incorporated in the model as to allow more design analysis concerning constructability concepts. Environmental and sustainable factors and attributes can be considered as such an addition. For example, the proposed model took into account the overall effect of weather conditions on designs where a more detailed examination of different environmental factors can make the analysis more precise. Also, sustainable factors aspects like thermal performance attributes or acoustical factors.

• The quantification process of factors can be improved by undergoing more surveys to assess the relative weights of the sub factors associated to constructability qualitative factors. For example sub factors associated with safety analysis are all assumed to be of equal weight, where if each sub factor had a specific relative weight their constructability score would have been more precise and reliable.
• For simplicity purposes the proposed platform included inputs from architectural components only. In real life scenarios, more constructability problems can emerge when mechanical and electrical components are fully integrated with architectural components in the BIM model. Thus, extending the developed BIM model to meet different engineering disciplines (M/E) can have an additional value to proposed platform.

• Consider to integrate a fifth dimension (4D + cost = 5D) to the model. This will lead to a better understanding and evaluation of constructability impact on design concerning financial analysis. Together, 4D and 5D models have the potential to study and evaluate design coordination, quantity takeoff, cost estimation, project scheduling, and production control.

• This research studied in detail constructability assessment of designs during the design phase. In spite of the fact that maximum constructability payback can be achieved during the preconstruction phase, a good enhancement to this approach is to upgrade the proposed platform so that the analysis can be done throughout all construction phases. To fix certain constructability issues, actual and up-to-date data input rather than assumed inputs imported to a virtual model are needed. These kinds of data cannot be gathered during the preconstruction phase.

• Apply the proposed methodology to other construction types (airports, industrial projects, roads, etc…). Constructability principles definitely changes from one building type to another since designs are generated based on function constrains. From this perspective, if the proposed platform is to be modified to be applicable
to various building types, more benefits can be achieved to the construction industry.

- Enhance the prototype Access-based tool in order to allow the user to modify design, construction, and site impacts factors from within the tool itself. The proposed tool has a limited number of interface modification options. Upgrading this limitation to allow users to add, remove or change predefined factors and attributes to meet specific project team’s requirements can provide better analysis and representation of the results.
Ch VII. References


### APPENDIX A.1: BUILDABLE DESIGN APPRAISAL SYSTEM

| Buildability Score of Structural System (Including Roof System) + Buildability Score of Wall System + Buildability Score of Other Buildable Design Features |
|---|---|---|
| $BS$ | $= 50 \left( \sum (A_s \times S_s) \right) + 40 \left( \sum (L_w \times S_w) \right) + N + \text{Bonus points}$ |

where $A_s = \frac{A_{sa}}{A_s}$

$L_w = \frac{L_{wa}}{L_{wt}}$

$A_s$ = Percentage of total floor area using a particular structural system

$A_{sa}$ = Total floor area which includes roof (projected area) and basement area

$A_{sa}$ = Floor area using a particular structural system

$L_s$ = Percentage of total external & internal wall length using a particular wall system

$L_{sa}$ = Total wall length, excluding the length of external basement wall for earth retaining purpose

$L_{wa}$ = External & internal wall length using a particular wall system

$S_s$ = Labour saving index for structural system (Table 1)

$S_w$ = Labour saving index for external & internal wall system (Table 2)

$N$ = Buildability Score for other buildable design features (Table 3)

**Bonus points** = Bonus points for the use of single integrated components

The Buildability Score of a project which consists of more than one building should be computed by multiplying the respective Buildability Score of the individual building with its percentage of the total floor area of that building in the project. That is,

$$BS_{\text{project}} = \text{Sum of} \left( BS_{\text{building}} \times \left( \frac{A_s}{A_{sa}} \right)_{\text{building}} \right) / \left( \frac{A_s}{A_{sa}} \right)_{\text{project}}$$

---

Figure A-1-1: Buildability Score Formula (BCA, 2005-a)
APPENDIX A.2: HONG KONG BUILDABILITY SCORE SYSTEM

Buildability Score of a project =

\[ X_1 \sum (V_1 \times BI_{Li}) + X_2 \sum (A_1 \times BI_{Li}) + X_3 \sum (A_2 \times BI_{Li}) + X_4 \sum (A_3 \times BI_{Li}) + X_5 \sum (A_4 \times BI_{Li}) + X_6 \sum (A_5 \times BI_{Li}) \]

\[ + X_7 (BS_{finishing}/100) + X_8 \sum (BL_{sp} \times conv_{sp})/\text{Sum of all BL}_{sp} \]

\[ + X_9 \sum (BL_{envelope} \times conv_{envelope})/\text{Sum of all BL}_{envelope} \]

\[ + X_{10} \sum BI_{Ext}/\text{sum applicable max.} \]

\[ + X_{10} \text{ Bonus (10 points for other innovations improving buildability)} \]

Notes:

* Buildability score for finishing systems adopted = BS\_building =

\[ Z_1 \sum (A_{nc} \times BI_{nc}) + Z_2 \sum (A_{fc} \times BI_{fc}) - Z_3 \sum (A_{envelope} \times BI_{envelope}) + Z_4 \sum (A_{roof} \times BI_{roof}) + Z_5 \sum (A_{wall} \times BI_{wall}) \]

where

- \( V_1 \) = Percentage of total volume of major structural components using a particular structural frame design
  
- \( A_1 \) = Percentage of total construction floor area using a particular slab design
  
- \( A_2 \) = Percentage of total elevator area using a particular envelope design
  
- \( A_3 \) = Percentage of total plan area using a particular roof design
  
- \( A_4 \) = Percentage of total elevation area using a particular internal wall design

Figure A-2-1: Buildability Score Formula for Hong Kong (Wong, 2007)
where

\[ A_{iw} = \text{Percentage of total elevation area applying a particular finishing system at internal walls} \]

i.e. (Elevation area applying a particular finishing system at internal walls / Total finishing areas at internal walls) \times 100\%

\[ A_{if} = \text{Percentage of total construction floor area applying a particular finishing system at internal floors} \]

i.e. (Construction floor area applying a particular finishing system at internal floors / Total areas of internal floors) \times 100\%

\[ A_{ic} = \text{Percentage of total construction area applying a particular finishing system at internal ceilings} \]

i.e. (Construction area applying a particular finishing system at internal ceilings / Total areas of internal ceilings) \times 100\%

\[ A_{ew} = \text{Percentage of total elevation area applying a particular finishing system at external walls} \]

i.e. (Elevation area applying a particular finishing system at external walls / Total areas of external walls) \times 100\%

\[ A_{ec} = \text{Percentage of total plan area applying a particular finishing system at roof coverings} \]

i.e. (Plan area using a particular finishing system at roof coverings / Total plan areas at roof coverings) \times 100\%

\[ BI_x = \text{Buildability index for a particular structural frame design} \]

\[ BI_y = \text{Buildability index for a particular slab design} \]

\[ BI_e = \text{Buildability index for a particular envelope design} \]

\[ BI_r = \text{Buildability index for a particular roof design} \]

\[ BI_w = \text{Buildability index for a particular internal wall design} \]

\[ BI_{ws} = \text{Buildability index for a particular finishing system at internal walls} \]

\[ BI_{if} = \text{Buildability index for a particular finishing system at internal floors} \]

\[ BI_{ic} = \text{Buildability index for a particular finishing system at internal ceilings} \]

\[ BI_{ew} = \text{Buildability index for a particular finishing system at external walls} \]

\[ BI_{ec} = \text{Buildability index for a particular finishing system at external ceilings} \]

\[ BI_{rs} = \text{Buildability index for a particular roof covering system} \]

\[ BI_{sx} = \text{Buildability index for a particular building services aspect} \]

\[ BI_{bf} = \text{Buildability index for a particular building feature} \]

\[ BI_{sf} = \text{Buildability index for a particular site specific factor} \]

\[ \text{cov}_{sf} = \text{Percentage coverage for a particular building services aspect} \]

\[ \text{cov}_{bf} = \text{Percentage coverage for a particular building feature} \]

\[ \text{Sum of all } BI_{bf} = \text{Sum of all buildability indices of building features} \]

\[ \text{Sum of all } BI_{sx} = \text{Sum of all buildability indices of building services aspects} \]

\[ \text{Sum of all } BI_{sf} = \text{Sum of all buildability indices of site specific factors applicable to the project} \]

\[ X_1 \text{ to } X_5 = \text{Buildability Weightings for different design components} \]

\[ Z_1 \text{ to } Z_5 = \text{Buildability Weightings for different finishes locations} \]

FIGURE A-2-2: Buildability Score Formula for Hong Kong (Wong, 2007) Cont'd
# APPENDIX A.3: CONSTRUCTABILITY ASSESSMENT

## FRAMEWORK

<table>
<thead>
<tr>
<th>Factors</th>
<th>Measurement</th>
<th>Level of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assembly process</td>
<td>Total number of process</td>
<td>Very Low &gt;12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low 10-12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium 7-9</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High 4-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &lt;4</td>
</tr>
<tr>
<td>Rebar Assembly</td>
<td>Reinforcement Ratio (%)</td>
<td>Very Low &gt;4.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low 3.0% - 4.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium 2.0% - 3.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High 1.0% - 2.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &lt;= 1.0%</td>
</tr>
<tr>
<td>Structural Bay</td>
<td>B /BY x 100</td>
<td>Very Low &lt;= 20%</td>
</tr>
<tr>
<td>Dimensioning</td>
<td>Where: B = total # of bays with</td>
<td>Low &gt;20% - 40%</td>
</tr>
<tr>
<td></td>
<td>the most common dimensions</td>
<td>Medium &gt;40% - 60%</td>
</tr>
<tr>
<td></td>
<td>BY = total # of bays</td>
<td>High &gt;60% - 80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &gt;80%</td>
</tr>
<tr>
<td>Formwork Utilization</td>
<td>F / N x 100</td>
<td>Very Low &gt;80%</td>
</tr>
<tr>
<td></td>
<td>Where: F = Total # of beams that</td>
<td>Low &gt;60% - 80%</td>
</tr>
<tr>
<td></td>
<td>require formwork</td>
<td>Medium &gt;40% - 60%</td>
</tr>
<tr>
<td></td>
<td>N = Total # of beams</td>
<td>High &gt;20% - 40%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &lt;=20%</td>
</tr>
</tbody>
</table>

## TABLE 0-2: Measures of Trade Variability (Zin Et Al., 2004)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Measurement</th>
<th>Level of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade Variability</td>
<td>Total number of trades</td>
<td>Very Low &gt;8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Low 7-8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Medium 5-6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>High 2-3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &lt;2</td>
</tr>
</tbody>
</table>

## TABLE 0-3: Measures of Specification (Zin Et Al., 2004)

<table>
<thead>
<tr>
<th>Factors</th>
<th>Measurement</th>
<th>Level of Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specifications</td>
<td>S / N x 100</td>
<td>Very Low &lt;= 20%</td>
</tr>
<tr>
<td></td>
<td>S = total # of beams with normal</td>
<td>Low &gt;20% - 40%</td>
</tr>
<tr>
<td></td>
<td>specifications</td>
<td>Medium &gt;40% - 60%</td>
</tr>
<tr>
<td></td>
<td>N = Total # of beams</td>
<td>High &gt;60% - 80%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Vey High &gt;80%</td>
</tr>
</tbody>
</table>
APPENDIX A.4: CONSTRUCTABILITY ASSESSMENT
COGNITIVE TASKS

Figure A-4-1: A Typical Task Reduction in Evaluating Constructability of a Design
(Ugwu et al., 2004)
APPENDIX A.5 : Fuzzy Quality Function Deployment

Figure A-5-1: House of Quality for Buildable Design (Yang et al., 2003)
FIGURE A-5-2: Triangular Fuzzy Numbers (Yang et al., 2003)
Appendix B: Data Collection

APPENDIX B.1 : SAMPLE QUESTIONNAIRE

Survey of Level of Importance of Factors Affecting Constructability

Constructability relates to the extent to which a design fulfills efficient use of construction resources and enhances ease and safety of construction on site within the client's requirements and cost.

In order to improve the constructability of buildings we have to establish a quantified model to measure constructability.

Objective of this survey is to identify the level of importance of various attributes of constructability in Canada, in order that a suitable measure of constructability can be established.

<table>
<thead>
<tr>
<th>Contact Name (optional):</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Profession:</td>
<td>Architect</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Please perform a pairwise comparison of importance using the following 1 to 9 scale:

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equally Preferred</td>
<td>Strongly Preferred</td>
<td>Extremely Preferred</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Example**

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

A is Extremely Preferred to B. A is Equally Preferred to C.

**The Survey**

With Respect to ...

<table>
<thead>
<tr>
<th>Impacts</th>
<th>See impacts.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standards</td>
<td>Standardization</td>
</tr>
<tr>
<td>Standardization</td>
<td>Standards Impact of Design</td>
</tr>
<tr>
<td>Accessibility</td>
<td>Accessibility During Construction</td>
</tr>
<tr>
<td>Accessibility During Construction</td>
<td>Accessibility Consideration</td>
</tr>
<tr>
<td>Costs</td>
<td>Cost Consideration</td>
</tr>
<tr>
<td>Cost Consideration</td>
<td>Cost of Constructability</td>
</tr>
<tr>
<td>Constructability</td>
<td>Installation Sequence</td>
</tr>
</tbody>
</table>

Your Cooperation is Highly Appreciated!!!

Figure B-1-1: Sample Questionnaire
Appendix C: BIM Output

APPENDIX C.1: BIM AUTOMATIC QUANTITIES TAKE OFF

<table>
<thead>
<tr>
<th>Door Schedule</th>
<th>Count</th>
<th>Family and Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>158</td>
<td>M_Bifold-2 Panel: 0915 x 2134mm</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>M_Single-Flush: 0762 x 2134mm</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>M_Single-Flush: 0964 x 2134mm</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>M_Single-Flush: 0915 x 2134mm</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>M_Single-Flush: 0915 x 2134mm Steel Roof</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>M_Single-Glass 1: 0762 x 2134mm</td>
</tr>
<tr>
<td></td>
<td>31</td>
<td>M_Sliding-2 Panel: 1830 x 2134mm</td>
</tr>
<tr>
<td>Grand total:</td>
<td>341</td>
<td></td>
</tr>
</tbody>
</table>

Figure C-1-1: BIM Snapshot - Door Schedule

<table>
<thead>
<tr>
<th>Wall Material Takeoff</th>
<th>Material Name</th>
<th>Family and Type</th>
<th>Width</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Air Barrier - Air Infiltration Barrier</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Default Wall</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Masonry - Concrete Block</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Metal - Stud Layer</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Misc. Air Layers - Air Space</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Plasterboard</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Wood - Sheathing - plywood</td>
<td>Basic Wall. Exterior - Brick on Mill. Brick Clad</td>
<td>0.298</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>Air Barrier - Air Infiltration Barrier</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Default Wall</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Masonry - Brick</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Metal - Stud Layer</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Misc. Air Layers - Air Space</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Plasterboard</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Wood - Sheathing - plywood</td>
<td>Basic Wall. Exterior - Brick on Mill. Stud</td>
<td>0.298</td>
<td>84</td>
</tr>
<tr>
<td></td>
<td>Concrete - Cast-in-Place Concrete</td>
<td>Basic Wall. Foundation - 300mm Concrete</td>
<td>0.300</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Concrete - Cast-in-Place Concrete</td>
<td>Basic Wall. Foundation - 300mm x 1m</td>
<td>0.300</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Masonry - Brick</td>
<td>Basic Wall. Generic - 90mm Brick</td>
<td>0.030</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Gypsum Wall Board</td>
<td>Basic Wall. Interior - 123mm Partition (1-hr)</td>
<td>0.124</td>
<td>331</td>
</tr>
<tr>
<td></td>
<td>Metal - Stud Layer</td>
<td>Basic Wall. Interior - 123mm Partition (1-hr)</td>
<td>0.124</td>
<td>331</td>
</tr>
<tr>
<td></td>
<td>Gypsum Wall Board</td>
<td>Basic Wall. Interior - 135mm Partition (2-hr)</td>
<td>0.137</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>Metal - Stud Layer</td>
<td>Basic Wall. Interior - 135mm Partition (2-hr)</td>
<td>0.137</td>
<td>115</td>
</tr>
<tr>
<td></td>
<td>Concrete - Cast-in-Place Concrete</td>
<td>Basic Wall. Retaining - 300mm Concrete</td>
<td>0.300</td>
<td>46</td>
</tr>
<tr>
<td>Grand total:</td>
<td>1917</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure C-1-2: BIM Snapshot - Wall Material Schedule
Figure C.2.1: BIM Model Showing Internal Building Components

Figure C.2.2: BIM Model Showing Sectional Details
<table>
<thead>
<tr>
<th>Task Name</th>
<th>Duration</th>
<th>Start</th>
<th>Finish</th>
<th>Milestone</th>
<th>External Milestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Partitioning</td>
<td>4 days</td>
<td>Fri 15/3/99</td>
<td>Mon 19/3/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GF Ceiling work</td>
<td>4 days</td>
<td>Wed 17/3/99</td>
<td>Thu 24/3/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st FL Finishing</td>
<td>70 days</td>
<td>Wed 12/4/99</td>
<td>Tue 16/4/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd FL Finishing</td>
<td>70 days</td>
<td>Mon 19/4/99</td>
<td>Fri 23/4/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>140 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st FL Finishing</td>
<td>70 days</td>
<td>Wed 12/4/99</td>
<td>Tue 16/4/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2nd FL Finishing</td>
<td>70 days</td>
<td>Mon 19/4/99</td>
<td>Fri 23/4/99</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>140 days</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure C-3: Time Schedule Used For Case Study
Appendix D: Case Study

APPENDIX D.1: 2D PLANS SAMPLES FOR CASE STUDY

Figure D1-1: Plan Sample #1

Figure D1-2: Plan Sample #2