# BIM.04

# Constructability Assessment Using BIM/4D CAD Simulation Model

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**ABSTRACT**—Implementation of constructability/buildability ideas in the construction industry has a potential return on investment concerning time and money. Literature shows that quantified assessment of constructible designs provides benefits to the owners, contractors, and designers. The potential use of new technology-based tools to assess constructability of a design has not been fully realized. A new methodology to evaluate the level of application of constructability principles in residential buildings was proposed. This methodology integrates the object-oriented Building Information Model (BIM) and the 4D CAD simulation model. Factors affecting constructability of building designs in Canada are identified from a questionnaire survey on constructability attributes. Multi-attribute decision analysis and Analytical Hierarchy Process (AHP) were used to assess the overall constructability value. The new methodology was validated using a case study of a condo project in downtown Montreal. The outcome showed that integrating BIM with 4D CAD simulation models has many benefits to designers in which evaluation of different designs can be done in a more accurate and faster way

**KEY WORDS**: 4D CAD, Analytical Hierarchy Process, BIM, constructability/buildability, design, and investment

The construction industry, because of its fragmented nature, separates practitioners with different expertise and disciplines. This segregation feature has caused misunderstanding and lessened productivity. This is obvious under the traditional procurement system, whereby contractors are only brought in after design completion. The Business Roundtable reported a potential return on investment of 10:1 by applying constructability [5]. The idea was to minimize the gap between what designers draw in offices and what contractors execute on sites. Analysis of case studies has proved that savings as much as 10.2 percent in project time and 7.2 percent in project cost can be achieved by applying constructability practices [21]. Also, carrying out constructability principles on building designs can have many benefits to owners and designers [3].

Many researchers have explored constructability to understand its implementation to the construction industry, mainly the Construction Industry Institute (CII) and the American Society of Civil Engineer (ASCE) [20]. By reviewing current literature, F.W. Wong and others found that quantified assessment of design is the best approach to improve constructability of designs [25].In 2007 the ASCE Constructability and Construction Research Council reported in a special publication "…the potential of new technology-based tools such as 4D CAD or BIM have not been fully realized. This area could also include validation of new constructability software tools" [9].

Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering and construction (AEC) industry. BIM facilitates a more integrated design and construction process that results in better quality buildings at lower cost and reduced project duration [8]. Another promising development is the four-dimensional (4D) Computer Aided Design (CAD) models that allow design and construction professionals to test different design and sequencing alternatives. 4D models are models that link each design unit to its corresponding time schedule. A symbolic object-oriented 4D model has the potential to support automated constructability reasoning and helping a project team in identifying constructability issues early in the design and construction phases [13].

This paper proposed a new methodology to measure the level of application of constructability principles on building designs using BIM and 4D models. The analysis of previous assessment methods revealed a lack of a clear and an accurate way to measure constructability. This research argued the idea that object oriented models have the potential to quantify the application of constructability factors were designers may have a fast, simple and a precise tool to analyze their designs. This paper proposed a new methodology to measure the level of application of constructability principles on building designs using BIM and 4D models. The following sections discuss the proposed framework followed by a brief description on a case study done on a condo project in downtown Montreal.

**Relevant Literature**

CII defined the term constructability as, "The optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" [6]. Similarly the CIRIA defined term buildability as, "The extent to which the design of a building facilitates ease of construction, subject to overall requirements for the completed building" [7]. Practitioners used the two terms interchangeably during different research areas. For this research, authors will use the term constructability throughout this paper.

Initially, construction managers display the benefits of constructability in terms of cost saving within the range of 1 to 14 percent of the capital cost [11]. The more researchers carried out studies on constructability, the more they identified benefits in terms of time, quality, and safety, as well as intangible bonuses [12]. As for constructability improvement, quantifying assessment of designs has proven to be the most common approach [25]. Hei developed and implemented an empirical system for scoring buildability of designs in the Hong Kong construction industry [14]. The Singaporean government introduced the Buildable Design Appraisal System (BDAS) where a mathematical model was developed based on standardization, simplicity and single integrated elements. 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 [27]. A cognitive model for buildability assessment based on knowledge mining and protocol analysis was established by O. Ugwu and others [23]. A fuzzy quality function deployment system for buildability design decision was elaborated by Y.Q. Yang and others to model constructability implementation on a given design [26]. Limitations to the preceding researches were recorded. Mathematical models needs trustworthy benchmarks to evaluate the assessed score, these benchmarks are time-consuming and rely on governmental statistics [14]. Time factor was not presented, thus analyzing the sequence of installed components cannot be done. The fuzzy models are a demanding assessment models were the user must assign many attributes: weight factors, client satisfaction indices, buildability aspects values etc [14].

Regarding the stages of implementation, constructability focuses itself at the design stage [6]. A big obstacle in getting true data integration through the life cycle of a building project has been the lack of proper integration of design information from the design team to the construction team. Even under the best circumstances, whatever the design team delivers to the contractors, the engineers must adjust the construction documents to achieve true constructability [18].

**Proposed Methodology**

The design of buildings requires the integration of many kinds of information into an artificial single model. An integrated process, or "whole building" design process, includes the active and continuing participation of users, code officials, building technologists, cost consultants, civil engineers, mechanical and electrical engineers, structural engineers, specifications specialists, and consultants from many specialized fields. The best buildings result from active, consistent, organized collaboration among all players [1]. This paper does not aim to discuss this integrated design process, but the proposed assessment methodology will be based on an integrated project delivery system.

Before introducing the new method, let’s take a look at certain terminologies which formed the bases of this concept. The first term to start with is “3D object-oriented, AEC-specific CAD “, which was used by Autodesk to describe BIM theories. It is agreed on that object oriented models and BIM are common names for a digital representation of the building process to facilitate exchange and interoperability of information in digital format. From this concept, the idea of Virtual Design and Construction (VDC) which is the use of integrated multidisciplinary performance models of design construction projects arouses [15].

The Industry Foundation Classes (IFC) is an object oriented file format with a data model developed by the International Alliance for Interoperability (IAI) to facilitate interoperability in the building industry. The IFC data model is a neutral and open specification that is not controlled by a single vendor or group of vendors. Also it is a commonly used format for Building Information Modeling (BIM). The IFC model specification is open and available because of its focus on ease of interoperability between software platforms [24]. The Danish government has made the use of IFC format(s) compulsory for publicly aided building projects [10].

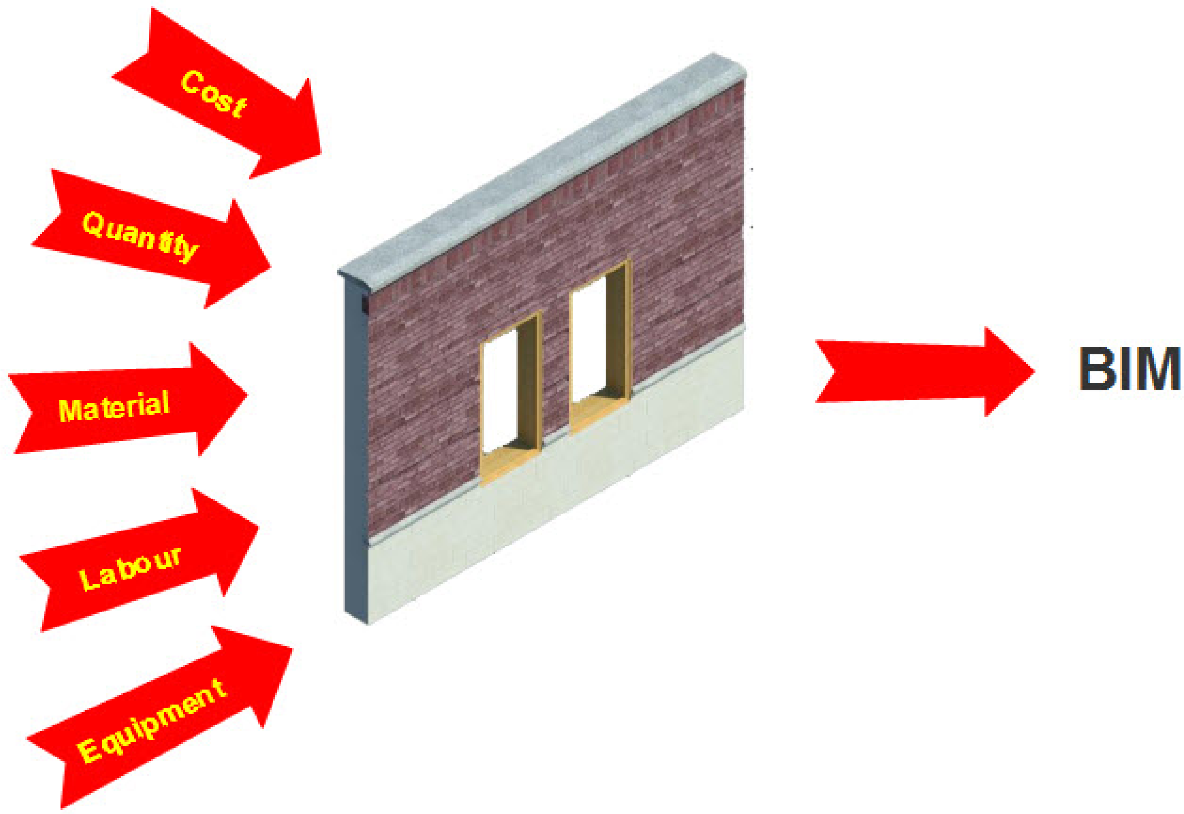


**Figure 1—Building Data Model**

Traditional 2-D and 3-D 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 building model, and will include the suitable relationships to walls; ceilings, floors, and so on. Thus, information about spaces that will be needed for constructability analysis can be easily obtained from an application using a building data model (See figure 1), whereas several complex calculations will be required to derive the same information from an application using a geometric data model [16]. The proposed framework is based on the integration of constructability design principles and building information modeling. Throughout excessive literature readings, 18 different design-relevant attributes were identified and distributed to six main groups. These groups constitute the main factors that affect constructability of building design. The next step was to assign weights to all the factors throughout a questionnaire survey based on the Analytic Hierarchy Process (AHP) technique. The AHP method is used to convert subjective assessments of relative importance to a set of overall scores or weight [22]. This method deals with a complex decision according to the weight of criteria. It is suitable for decisions with both quantitative and qualitative criteria [4].

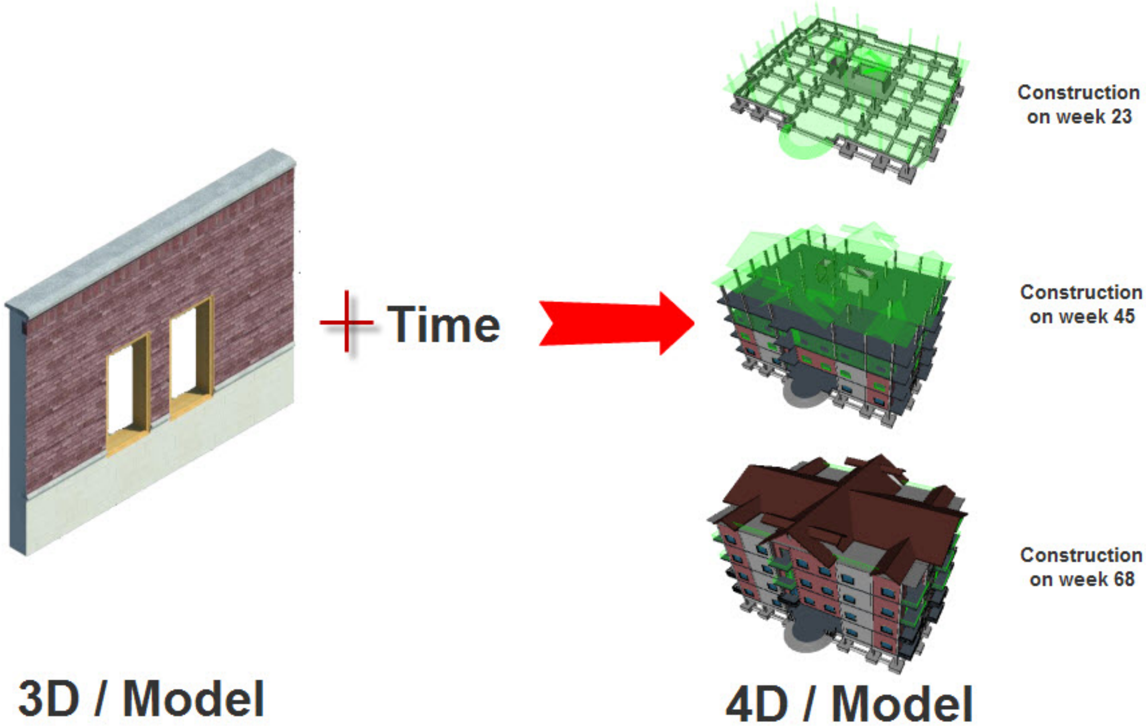


**Figure 2—Snapshots of a 4D Model Simulator**

A BIM model was generated using Autodesk product; Revit 2009. Building components like walls, materials, components are identified and drawn as object oriented elements. Building construction data like resources needed, time schedule, costs are linked to their corresponding elements using IFC modules already defined in the Revit software. Certain factors need to have custom modified IFC modules; these factors will be discussed in detail in following publications. 4D models are models that link the 3D description of a product to be constructed with the plan and time-based schedule to build it in order to show the animation of the construction of a project [15]. A preliminary time schedule was formed and linked to its matching component in the BIM model; thus a 4D model using NavisWorks Manage 2009 is generated. This model simulated virtual construction of the building so that every design component was tested and evaluated, minimizing unexpected problems when construction starts on site. Quantitative and qualitative data from BIM and 4D models are linked to the previous identified 18 constructability factors using Access 2007 data models. Figure 3 summarizes the overall evaluation framework.

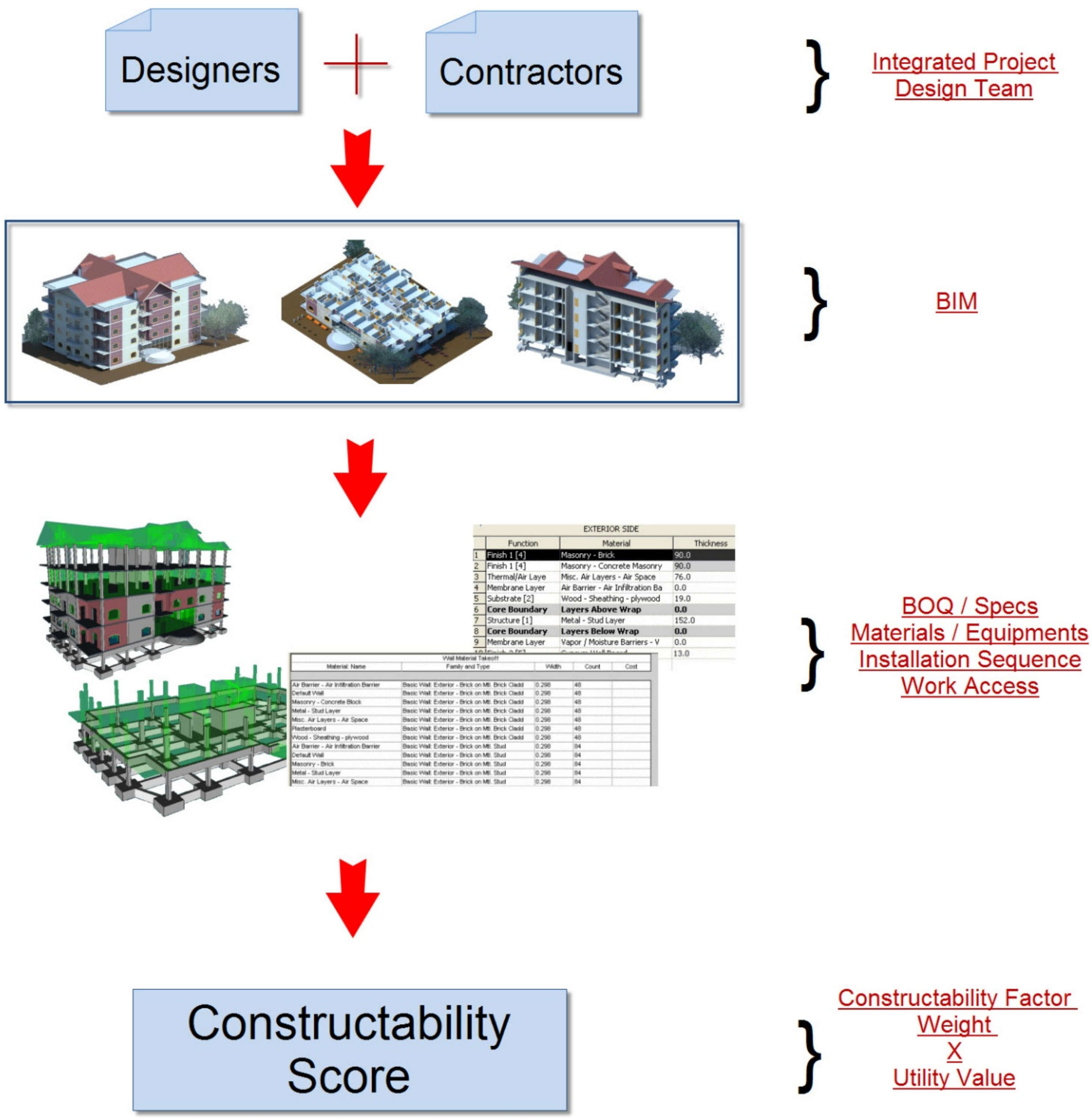


**Figure 3—Proposed Methodology for Constructability Assessment**

The assessment method developed is based on the calculations of two techniques AHP and Simple Multi-Attribute Rating Technique (SMART). The SMART is a multi-criteria decision analysis method that was developed by Von Winterfeldt in 1986 [17]. This method is a simple implementation of the Multi-Attribute Utility Theory (MAUT) in linear format [4]. Design components and construction specifications from BIM and 4D models are evaluated by the integrated design team using a five-point scale from very bad to very good, which are converted to utility values ($U_F$) between 0 and 1. Each scale coefficient is multiplied by its corresponding constructability factor weight ($W_F$) to form a constructability index (Ci). The overall measure is the total summation of all the constructability indexes of all factors. This concept is illustrated in figure 4.

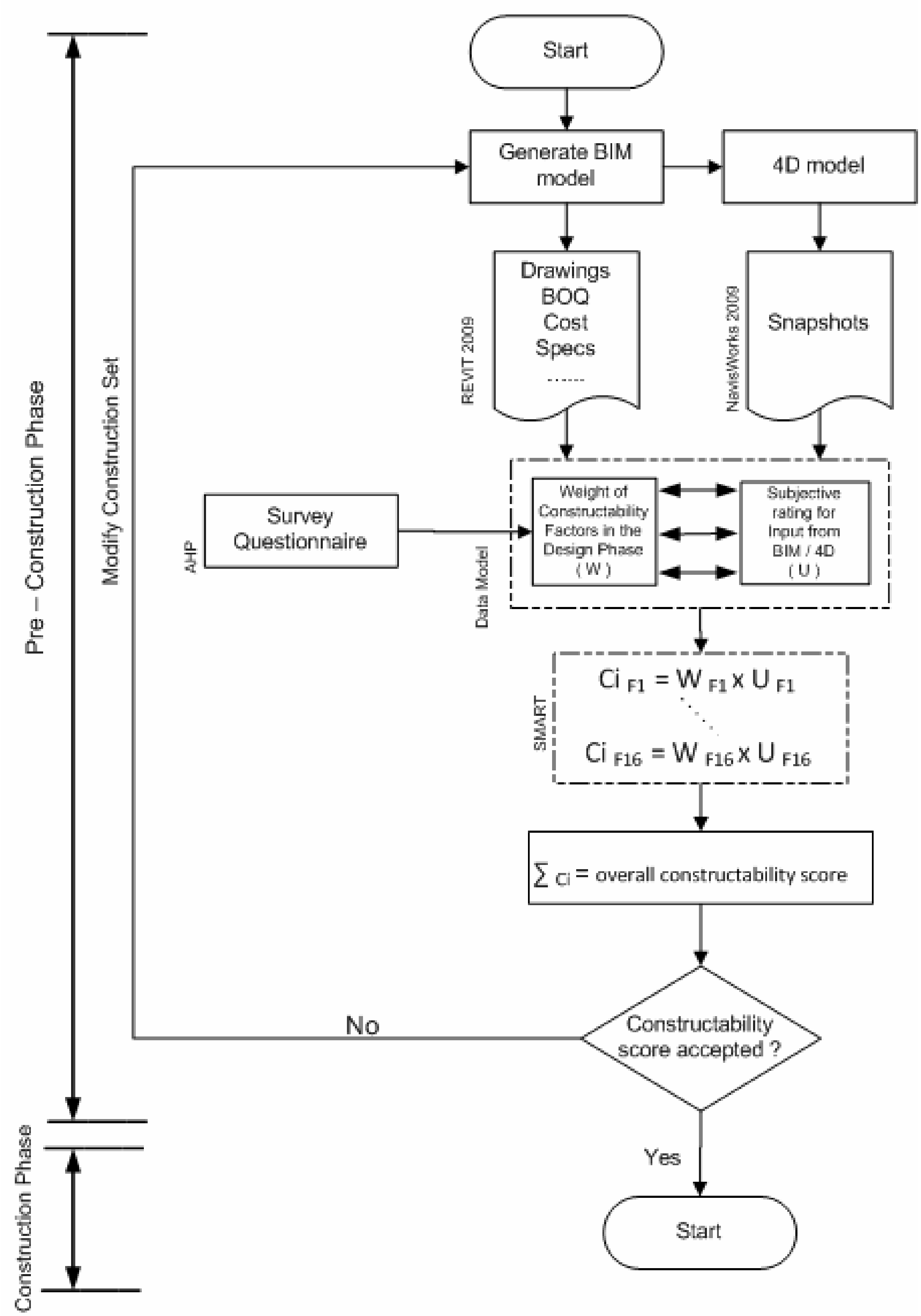


**Figure 4—Constructability Assessment In An Integrated Project Delivery System**

| Level # 1 | Level # 2 | Level # 3 | Input From BIM | Input From 4D | Factor Description |
|---|---|---|---|---|---|
| Design Attributes | Standardization | Prefabrication | X | | Precast Concrete, Prefabricated utility products, etc… |
| | | Grid Layout | X | | Horizontal / Vertical / Radial Grid dimensions |
| | | Standard Dimensions | X | | Dimensions for door, windows, partitions, tiles, etc… |
| | Economical Impact | Components' Flexibility | X | | Flexibility of movement of internal partitions (fixed / mobile). |
| | | Resources' Availability | X | | Availability of materials or special equipments. |
| | | Labors' Skills | X | | Availability of special labor skills |
| Construction Attributes | Installation | Construction Sequence | | X | Sequence of installation of components. |
| | | Time under Ground | | X | Construction time under ground level. |
| | | Building Envelope | | X | Construction of the whole building envelope. |
| | | Weather Effect | | X | Effect of climate conditions on construction work. |
| | | Safety | | X | Effect of construction sequence of workers' safety. |
| | Space | Material Access | | X | Space for material storage and transportation on site. |
| | | Personnel Access | | X | Accessibility of equipments and tools for and from different site locations. |
| | | Equipment Access | | X | Accessibility of personnel for different site locations. |
| External Impacts | Utility Availability | Government Facilities | X | | Availability of governmental facilities like electrical and infrastructure services. |
| | | Roads use ability | | X | Applicability of public roads for transportation. |
| | Site Impacts | To Adjacent Sites | | X | Effect of current construction to adjacent constructions. |
| | | To Infrastructure | | X | Effect of current construction to adjacent or nearby infrastructure constructions. |

**Table 1—Factors Affecting the Impacts of Building Design on Constructability Constructability Factors Vs. BIM Components**

As previously discussed, each constructability factor must be linked to its corresponding BIM component in order to evaluate the whole model. Factors are gathered from previous researchers who worked with constructability knowledge acquisitions. Table 1 show in detail factors classification followed by their explanatory description concerning constructability aspects. For example, prefabrication of building component falls under standardization factor which is one of two main subcategories of the design attribute. The input for the quantitative data concerning this factor will be exported from the BIM model and imported to the data model generated in Access 2007 software. Similarly factor like accessibility of material access, will be analyzed from a 4D model where the sequence of executed activities can be visualized graphically and thus assessed subjectively using the SMART technique.
case study

To test the applicability of the earlier methodology, a condos project in Montreal was taken as a base for our case study. The project is a building with four floor levels, each level constitute of eight apartments, except for the first floor. Using BIM technology, sections, elevations and construction details are generated without human intervention using the parametric features found in the BIM vendor. Materials take off and components quantity are calculated automatically and exported to the data model to be included in the assessment evaluation. The basic benefits of a BIM-based methodology for our case study include the following three items.

- BIM allows a 3-D simulation of the building and its components, where we predicted elements, calculated materials, and time quantities.
- The ability to construct the building virtually before physical construction begins on site. And,
- The aptitude for contractors to share their construction experience with designers to minimize problems when real construction starts.

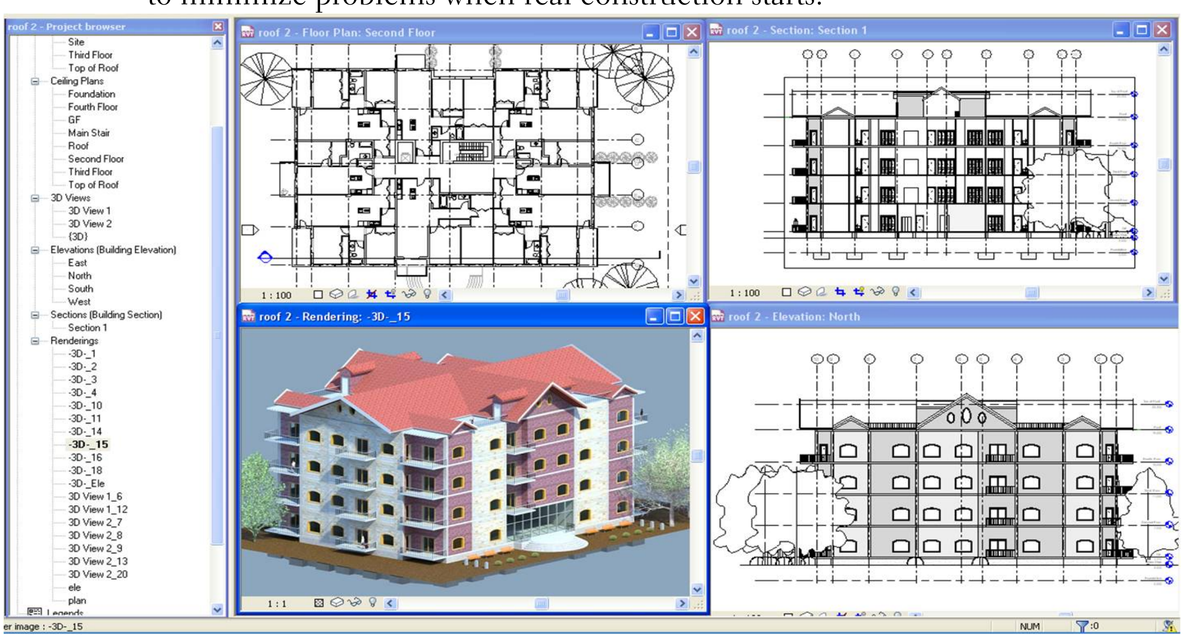


**Figure 5—Automatic Architectural Drawings Are Generated From A Single BIM Model**

This section will discuss briefly how BIM / 4D models were used to assess constructability of designs. The best way to test for constructability is to simulate the construction of building and visualize what might goes wrong when real construction starts. As discussed earlier BIM tools can achieve maximum payback when used in an integrated project delivery system where designers and contractors are involved together in building up the construction set. Scenario # 1 (See figure 6) will focus on the analyses of building envelopes. BIM illustrated the specific design components need to form the building skin by using a proper components filter. Quantitative values like material types and costs are exported to the data model using Access 2007. This data model will link various attributes and modules from BIM to their respective constructability factors where they will be measured and evaluated. Screenshots from the 4-D simulator will show how the proposed envelopes will acts when linked to other building systems.

Concerning the building envelopes, the following are some of the constructability factors than need to be measured.

- construction sequence;
- weather effect;
- material access;
- workers access, etc.

The consideration and detailing of a building shell, including the roof, should facilitate the enclosure of the building at the earliest possible stage so that work can be carried out without hindrance from inclement weather. Figure 6-b stresses this constructability concept where the construction manager can visualize the work done on the envelope and then figure out if the sequence is accepted or not. Numerous modifications can be done to the original planned time schedule until the work sequence is optimized as much as possible. Moreover, 4D snapshots illustrated active working spaces. This allowed worker and equipment access to different building locations to be planned, so there would be minimum problems. The efficient location and distribution of temporary work and storage areas is also necessary for good constructability. Accessibility of personnel, materials and equipments during construction is essential for constructability performance [2, 6]. Also designers should optimize the use of plant and equipment, taking their specific features and capacities into account [6].

Scenario #2 shows the analyses of another important building component, internal partitions. The design of these partitions may seem functionally to the designer and economically feasible to the owner, but a nightmare to contractors to construct. In order to assess properly this aspect the following constructability factors must be taken into consideration.

- material cost;
- material quantity;
- resources availability; and,
- components flexibility, etc.

As discussed, quantitative data will be linked automatically to their corresponding constructability factors and the 4D simulator, which can be adjusted on any given date, will simulate their construction sequence. The method of construction should encourage the most effective sequence of building operation to ensure good constructability. Moreover the design should arrange work sequencing in such a way that a trade can complete all its work at one location with minimum visits as possible [19]. In addition to this, a good constructible design should arrange work on site to be carried out in a workmanlike manner without risk of damage to adjacent finished elements and with minimum requirements for special protection.

Designers should use widely available and easily converted materials that can be worked on quickly and economically for optimization of constructability. The products and materials to be used must be proven suitable for the purposes, with which contractors recommendations should be complied [2]. Methods should be sought to improve constructability by designing for economical use of labor and widely available and versatile tools, plant and equipment [12].

Based on data exported from BIM / 4D models, the design team can analyze each constructability factor identified earlier in this paper and rate the compliance with constructability concepts from very bad to very good. These subjective values are converted to utility values between 0 and 1 (very bad = 0, bad = 0.25, moderate = 0.5, good = 0.75, very good = 1). A weighted criterion score (not shown) is obtained by multiplying the utility values by the normalized weight factors established from the questionnaire survey. The weighted criterion scores for both BIM and 4D inputs are summed into the overall final utility scores.

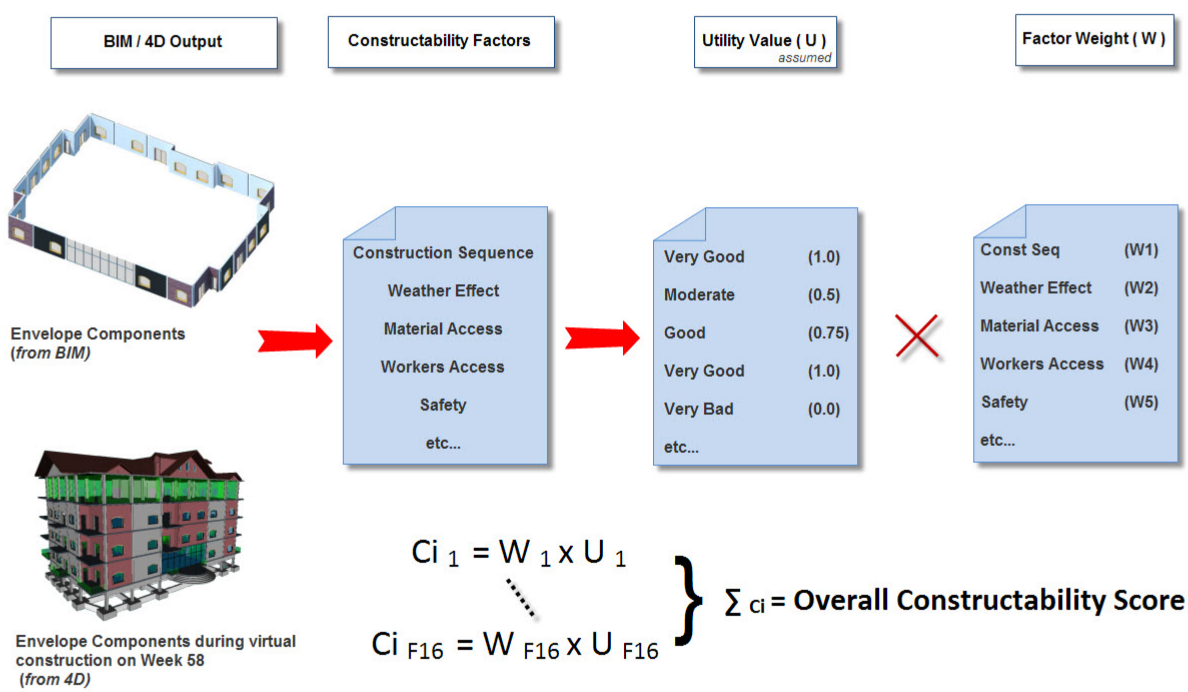


**Figure 6—Scenario # 1**

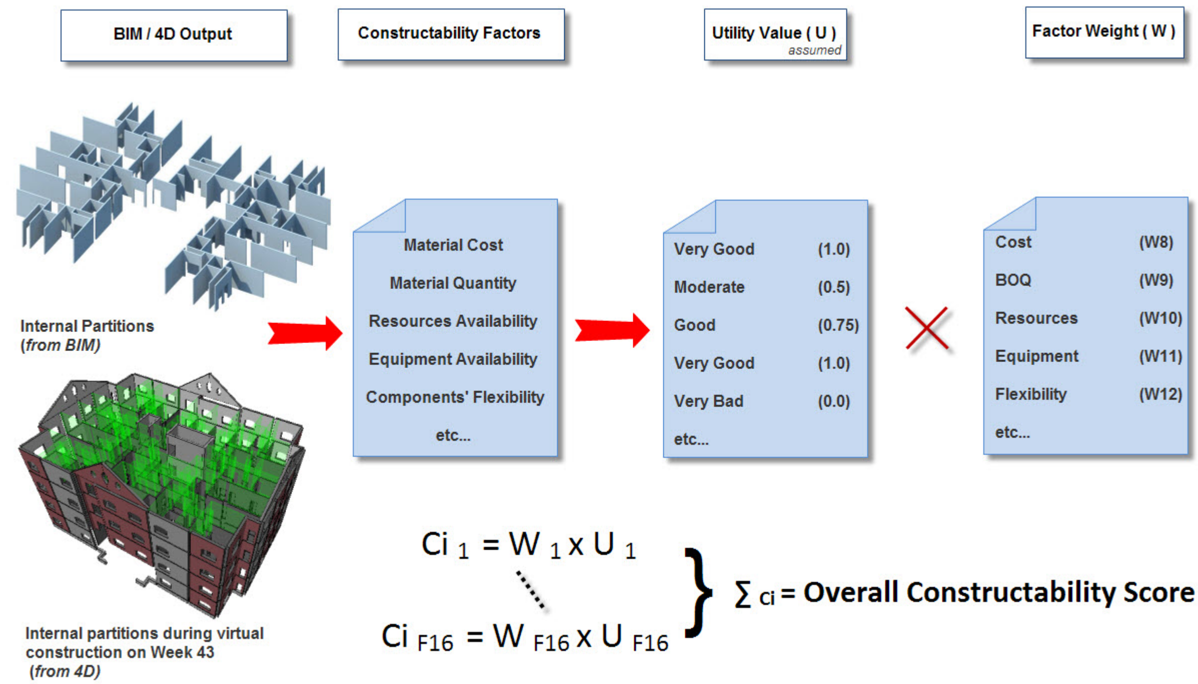


**Figure 7—Scenario # 2**

This paper introduced a new methodology to assess constructability of building design. The importance of such an assessment is documented throughout recent researches. Certain limitations were recorded concerning previous concepts to measure constructability. This paper argues the idea that BIM based models can be effective in generating a detailed virtual construction document, which facilitates the assessment of quantitative and qualitative data accurately. Two different assessment techniques were used: AHP and SMART. AHP converted subjective assessments of relative importance to set of overall weight for constructability factors affecting building design. SMART technique was used to scale the performance of any given design based on the inputs from BIM and 4D models. The application of this concept was demonstrated throughout a case study done on a condos building found in Montreal. BIM models were generated and a brief explanation was given to show how 4D models can be used to check for constructability factors. Further publications will show more applications with reference to the proposed concept. One of many benefits for using BIM technologies in such an assessment is the easiness and preciseness to modify the design. Because of the parametric capabilities found in BIM models any single change done to any specific object will be updated to the whole construction set automatically. This technological aspect gives the designers the freedom to optimize their designs as much as needed to achieve the best possible result.

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