A Reliability Model for BIM-Related Automated Processes

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Abstract
The use of Building Information Modeling (BIM) has changed the way professionals in design and construction do business. BIM is widely used for design, preconstruction planning, and construction tracking activities. As information technologies advance and new software offers more automation in these BIM processes, it is important for BIM users to assess the accuracy of automated results. This is especially needed in activities such as estimating, where the model is developed by designers and project risk for the contractor is tied to determining an appropriate cost of construction. This research aims to create a reliability model for quantitative assessment of automated BIM processes, such as estimating. Once completed, the reliability model will provide a tool for contractors to assess the accuracy of results from automated BIM processes. This paper discusses a brief background and history of automated BIM processes, the methodology for documenting needed historical data, and the statistical analysis in the current research.

Keywords: Building Information Modeling, Reliability Model, Automated Processes, Estimating

1 Introduction

In thinking about the use of Building Information Modeling (BIM) for material takeoff and cost estimation, it is important to consider the obstacles and challenges many contractors face in trusting the output of these models. As BIM grows in popularity and application, many contractors are realizing that the cost saving benefits can easily exceed the added cost of utilizing BIM on a project, thus causing more contractors to explore BIM utilization (Azhar et al 2011). When it comes to trusting automated BIM processes however, many contractors are showing great caution in taking full advantage of them. Unlike many other aspects of construction, the model is typically not contractually binding which leaves a degree of ambiguity concerning who is responsible for the accuracy of the data (Singh, Gu, and Wang 2011). Components of the model may also come from multiple parties that the contractor does not have any relationship with and depending on the project delivery method those parties may not be responsible for the model's content beyond design. This leaves the contractor with a mix of models from various sources that they then use for pre-construction and construction-related processes (Figure 1). This can lead to contractor mistrust of the information produced by the automated process, causing the contractor to spend additional time and money performing tasks that could have quickly been completed by automated BIM processes.

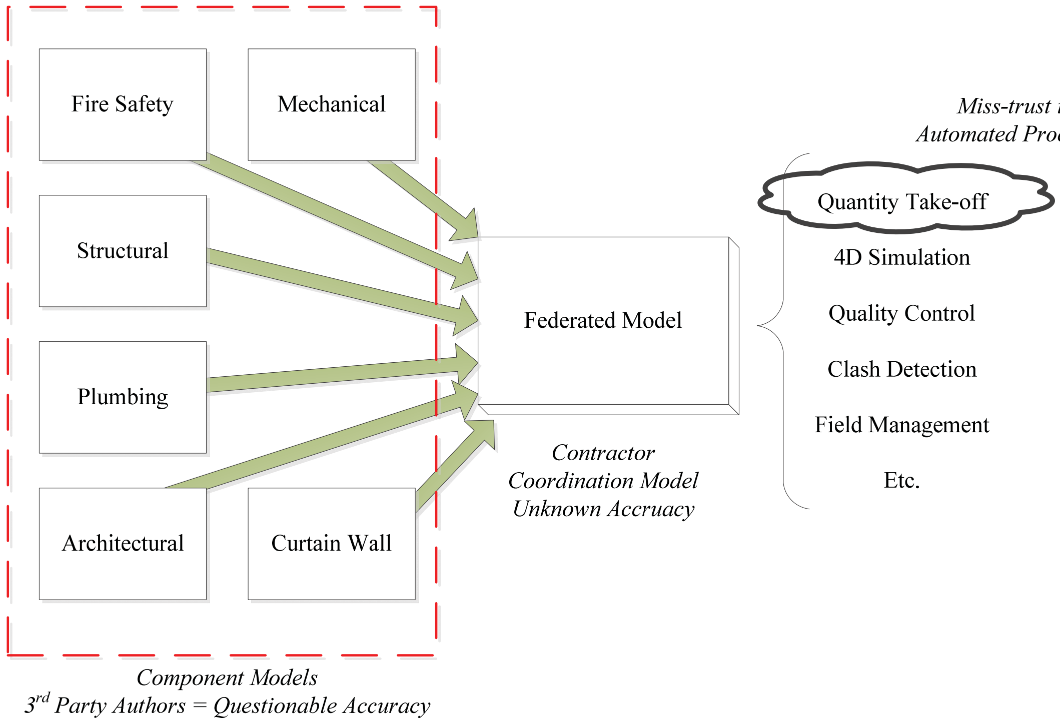

Figure 1 Typical Model Development

2 History, Benefits, and Challenges of Automated BIM Processes for Material Takeoff and Cost Estimation

From the first use of "building information modeling," or BIM by Jerry Laiserin in 2002 "as a description of the next generation of design software" (Laiserin 2002), BIM has evolved into a multi-application and multi-dimensional model of a construction project. Unlike traditional construction documents, a BIM model allows users continuous interface through the project life from design to construction, to facility management. Advanced from much simpler 3-D visualization and CAD applications that generate 3-D models through simple geometrical shapes, BIM uses "intelligent" geometry and objects that carry detailed information about them and interact with other objects in the building model (Smith & Tardif 2009; Eastman et al 2011).

Early applications of BIM focused heavily on the 3-D model aspects of the model that allowed architectural, engineering and construction (AEC) professionals to design and coordinate individual components of a building prior to the actual construction. As the implantation of BIM has grown, so has BIM's applications which include 3-D visualization; expedited production of fabrication/shop drawings; code reviews; forensic analysis; facilities management; cost estimating; construction sequencing; and conflict, interference and collision detection (Azhar et al 2011).

As the use of BIM has grown so has its benefits which include faster and more effective processes, better design, controlled whole-life costs and environmental data, better production quality, automated assembly, lifecycle data, cost savings, accurate and expedited cost estimates, and reduced construction schedule timeframe (Azhar et al 2011). The benefits of automated BIM processes for material takeoff and cost estimation can allow contractors to spend less time on material takeoffs and more time reviewing and planning the project. Because the BIM model often already contains and identifies individual components required for a project, a material takeoff can be performed by populating a detailed list of components. Cost can then be assigned to these components giving the contractor a detailed cost estimate of the project. Automated measurement can increase the speed of estimating and potentially improve accuracy of quantities when time is not available to carry out detailed takeoffs by hand (Tulke et al 2008).

A 2010 study of junior-level college students with prior course work in construction estimation showed significant improvement using BIM-assisted detailed estimating tools in terms of accuracy and efficiency when compared to the traditional manual estimating method. The test results also showed that the 3-D visualization function alone, as provided by the industry foundation classes, viewer-assisted estimating tool, was sufficient to generate perceivable improvements in both estimating efficiency as well as estimating accuracy (Shen & Issa 2010).

Even with all the benefits automated BIM processes can offer, the AEC industry has been slow to implement use of these processes due to the many challenges and obstacles often associated with them. The nature of BIM itself leads many challenges and obstacles including ownership, licensing, control, and responsibility of data entry of the BIM model(s). "The BIM on a project should be seen as a federation of different sub-models that have different names and that are created by different players on a construction project at different times, for different purposes, with different levels of detail and with different intentions. The various sub-models might typically include an architectural design model, structural design model, Mechanical/Electrical/Plumbing (MEP) design model, structural steel fabrication model, mechanical fabrication model, electrical fabrication model, plumbing fabrication model, site logistics model and so forth" (Reinhardt & Klancnik 2009).

Integration of these various sub-models along with the use of traditional contract documents can lead to challenges in trusting a model's accuracy and verifying the validity of data within the model (Azhar et al 2008). A traditional set of contract documents includes 2-D drawings with minimal 3-D renderings of the project and set of project specifications. Often these drawings and specifications include "standard" details and specification which may not be reflected in the BIM. Estimators lack confidence in automatically producing something that was previously controlled manually (McCuen 2008). Some of this comes from the loss of manual interpretation during the estimating process that is no longer there once this process is automated (Shen and Issa, 2010). This challenge is compounded further when liability for these inaccuracies is undefined by the contract documents (Sing, Gu, & Wang 2011).

Another obstacle often associated with automated BIM processes involves the manipulation of the data into a usable format for material takeoff and cost estimation. There is a need to develop automatic quantification that complies with the standard method of measurement rules (Olantunji, 2011). Although most native design software is capable of providing quantity takeoff tables, often a third-party application must be used to manipulate the data into a usable format. This manipulation can lead to conflicts with other model features making it impossible to extract quantities without adapting the model to some extent (Monteiro & Martins 2013).

3 Research Approach

The research currently underway focuses on developing a reliability model that contractors will be able to use to gain greater confidence in the accuracy of the automated BIM processes. The objective of this research is to synthesize expert opinions, historic model accuracy and error rates, construction cost databases, and established statistical reliability methods to create a rational process for checking and accepting output from automated material takeoff algorithms.

The research concept map in Figure 2 shows the vision of how the reliability model can help contractors gain a higher level of confidence in the results of automated processes.

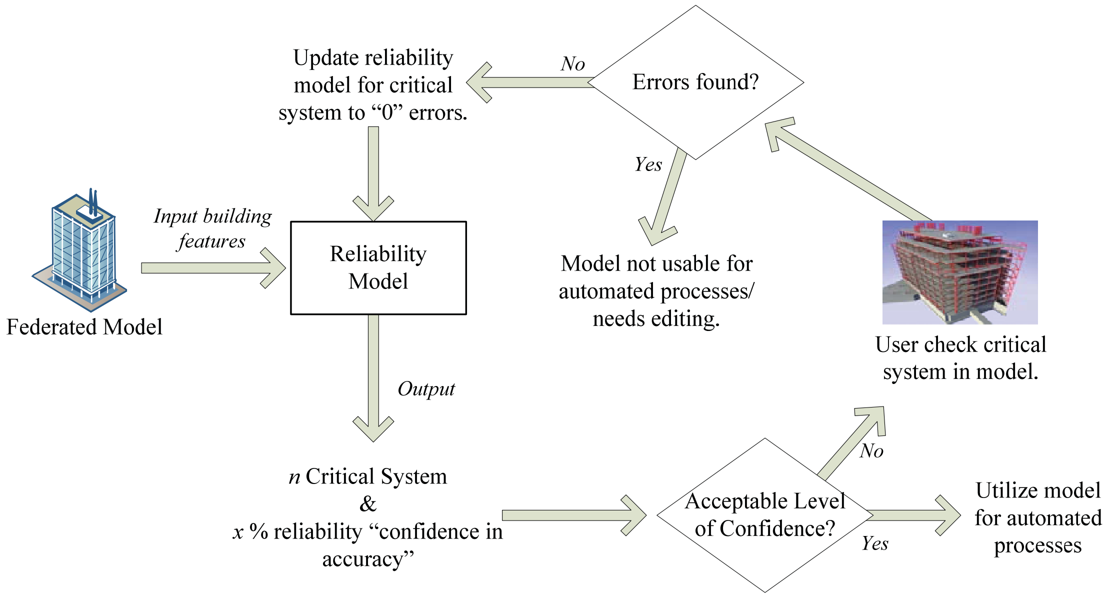

Figure 2 Research Concept Map

When the construction manager receives the different component models and creates a federated model, they can first input the features of the project into the reliability model. This information is used to calculate the reliability of the building based on the appropriate building type. For instance, items such as structural systems and cladding are input into the reliability model. Based on this information a confidence factor is generated for the systems and components present in the building; for instance, if a building is concrete, there is no need to consider steel framing in the analysis.

From here, the reliability model can identify key critical systems that historically cause the most risk financially and have the greatest history of error. The model can also give a reliability factor, or confidence in accuracy rating, based on the historical data. If that confidence level is adequate, the user can utilize the model for automated processes, however and more likely, if the user wishes to have a higher level of confidence they can check the federated model for the critical system. If errors are found, they can have the model edited or choose to not use the model for automated processes. (Note: the intention is for the user to get a feel for the model accuracy, not necessarily check every single piece, but a sample of objects until they can gauge their confidence that system is correct.) If no errors are found, the user can change that risk associated with the checked system to a "1" in the reliability model and a new confidence rating is produced. The cycle continues until the confidence rating is within the users acceptable tolerance for errors (much like a "waste factor" in a typical estimate).

4 Proof-of-Concept

The focus of this study was to develop a proof-of-concept of the proposed reliability model and statistical framework. Sample data, based on variations of two project's data, were used for the proof-of-concept of the reliability model. The data was organized through the UniFormat classification system by building component (Table 1) and included the overall project costs, to weight systems based on financial risk in order to give a standard "apple-to-apple" comparison, a cost breakdown for each system included in the building, historical rate of error within a building information model (by each system), and the acceptable rate of error that the user would accept from the model. It is worth noting that site-work and other specialized systems were intentionally left out due to the unique characteristics of these classifications. This would also mean that the total cost breakdowns for each project will not equal 100% of the project cost. This does not affect the statistical model. It would also allow for the use of partial project data if need be to identify trends of a specific system.

Table 1 Systems Included in Reliability Model Study

A1000.00 - Foundations	B1020.15 - Unit Masonry Structural Roof Frame	B2070.00 - Exterior Louvers and Vents	C1090.00 - Interior Specialties
A4000.00 - Slabs-On-Grade	B1020.16 - Other Structural Roof Frame (Please Specify)	B2080.00 - Exterior Wall Appurtenances (Accessories)	C2010.00 - Interior Wall Finishes
B1010.11 - Wood Framed Structural Floor Frame	B1020.21 - Wood Framed Roof Decks, Slabs, and Sheathing	B2090.00 - Exterior Wall Specialties	C2020.00 - Interior Fabrications
B1010.12 - Metal Framed Structural Floor Frame	B1020.22 - Metal Framed Roof Decks, Slabs, and Sheathing	B3010.10 - Steep Slope Roofing	C2030.00 - Flooring
B1010.13 - Cast-in-Place Concrete Structural Floor Frame	B1020.23 - Cast-in-Place Concrete Roof Decks and Slabs	B3010.50 - Low-Slope Roofing	C2040.00 - Stair Finishes
B1010.14 - Precast Concrete Structural Floor Frame	B1020.24 - Precast Concrete Roof Decks	B3010.60 - Other Roofing (Please Specify)	C2050.00 - Ceiling Finishes
B1010.15 - Unit Masonry Structural Floor Frame	B1020.25 - Other Roof Decks, Slabs, and Sheathing (Please Specify)	B3020.00 - Roof Appurtenances (Accessories)	C2090.00 - Interior Finish Schedules
B1010.16 - Other Structural Floor Frame (Please Specify)	B2010.10 - Exterior Wall Veneer	C1010.11 - Wood Framed Interior Partitions	D1000.00 - Conveying
B1020.11 - Wood Framed Floor Decks	B2010.21 - Exterior Wood Framed Wall Systems	C1010.12 - Metal Framed Interior Partitions	D2000.00 - Plumbing
B1020.12 - Metal Framed Floor Decks	B2010.22 - Exterior Metal Framed Wall Systems	C1010.13 - Cast-in-Place Concrete Interior Partitions	D3000.00 - Heating, Ventilation, and Air Conditioning (HVAC)
B1020.13 - Cast-in-Place Concrete Floor Decks, Slabs, and Toppings	B2010.23 - Exterior Cast-in-Place Concrete Walls	C1010.14 - Unit Masonry Interior Partitions	D4000.00 - Fire Protection
B1020.14 - Precast Concrete Floor Decks	B2010.24 - Exterior Precast Concrete Walls	C1010.20 - Interior Glazed Partitions/Storefronts	D5000.00 - Electrical
B1020.15 - Other Floor Decks, Slabs, and Toppings (Please Specify)	B2010.25 - Exterior Unit Masonry Walls	C1010.30 - Other Interior Partitions (Please Specify)	D6000.00 - Communications
B1020.11 - Wood Framed Structural Roof Frame	B2010.26 - Other Exterior Wall Systems (Please Specify)	C1020.00 - Interior Windows	D7000.00 - Electronic Safety and Security
B1020.12 - Metal Framed Structural Roof Frame	B2020.10 - Exterior Windows	C1030.00 - Interior Doors	E1000.00 - Equipment
B1020.13 - Cast-in-Place Concrete Structural Roof Frame	B2020.30 - Exterior Window Wall/Storefronts	C1040.00 - Interior Grilles and Gates	E2000.00 - Furnishings
B1020.14 - Precast Concrete Structural Roof Frame	B2050.00 - Exterior Doors and Grilles	C1070.00 - Suspended Ceiling Construction	

The variables for each system that are used in the statistical analysis are defined as:

- BIM Model Percent Accurate – The approximate percent accuracy between the BIM model and the contract documents used for construction. This value can be estimated based on past experience of a user or from aggregated historical data. The authors have recently begun collecting this information through surveys of construction companies using BIM for estimation. This is discussed in detail in section 4.2 of this paper.
- Percent of Project Cost – The cost of each component compared to the total project cost (note values in this column do not need to equal 100% as general conditions, etc. are not included in this study).
- Percent Quantity Error Acceptable – Allowable error +/- from actual material used. For example, if it was estimated to take 10 CY of concrete to pour a slab and it took 10.5 CY to actually construct it, the percent error would be 5% off of the estimate. The percent quantity error acceptable is the maximum percentage the quantity can be off and still be within acceptable limits.

4.1 Statistical Framework

A flexible statistical framework is designed to measure the reliability of an automated BIM process defined as the probability of producing results within a user-defined acceptable range. Because an automated BIM process generates estimates for each system of a building, our statistical framework involves measuring its reliability for each system. Table 1 lists the systems used during data collection. However, as can be seen, these systems have different dimensions. Therefore, to be able to conduct a ubiquitous analysis, without loss of generality, they are converted to a monetary value. The statistical framework is flexible in that it measures the reliability for any type of building such as concrete or steel. Pursuant to this goal, let $t \in \{1,2,..,T\}$ denote the building type, where T is the possible number of building types. Since systems that comprise a building may be different for different building types, we let the set $\{1,2,\dots,N_t\}$ denote the possible systems that comprise building type t. Note that hereafter, for ease of notation, we suppress the index t but it is clear that the approach is valid for any building type. First, the reliability of a system is determined. Let B denote the total number of buildings that their data is available and let w_i^b be the weight of system i for building b. From historic data for the buildings constructed in the past, one has the monetary estimates for each system from an automated BIM process as well as the actual budget used for that system. Therefore, one can estimate the error by considering the abovementioned difference. Let e_i^b be the error measured in monetary value occurred for system i and building b and τ_i^b be the maximum acceptable managerial error for system i and building b. Without loss of generality, we assume that the errors are in terms of absolute values and are nonnegative. Finally, let M^b denote the total budget for building b. Data for τ_i^b and M^b is collected from industry as part of the data collection phase of the project. X_i is defined as the expected weighted monetary error generated by an automated BIM process for system i. If the number of buildings in the survey is large enough (roughly greater than or equal to thirty), by the law of large numbers X_i has a normal distribution with mean (1)

$$\mu_i = \frac{\sum_{b=1}^{B} w_i^b e_i^b}{B} \quad (1)$$

and standard deviation (2)

$$\sigma_i^2 = \frac{\sum_{b=1}^{B} \left(w_i^b e_i^b - \mu_i\right)^2}{B-1} \quad (2)$$

that is (3),

$$X_i \sim N(\mu_i, \sigma_i^2). \quad (3)$$

Define R_i as the reliability of the automated BIM process for system i. Therefore, we have (4)

$$R_i = Prob\ (X_i < \tau_i), \quad (4)$$

where τ_i is the maximum acceptable monetary tolerance for system i and is calculated by (5)

$$\tau_i = \frac{\sum_{b=1}^{B} \tau_i^b M^b}{B}. \quad (5)$$

Note that in some application τ_i may be available directly from the data set provided by the managers. In this case, (5) is not used for its calculation, therefore, the reliability for system i is (6)

$$R_i = \varphi\left(\frac{\tau_i - \mu_i}{\sigma_i}\right), \quad (6)$$

where $\varphi(.)$ is the cumulative density function of the standard normal distribution.

So far the reliability estimates of an automated BIM process for a specific system were investigated. Next is to estimate the reliability of an automated BIM process. Since the reliability of an automated BIM process was modeled for each system by using a normal distribution, it is also possible to model the whole automated BIM process as a multivariate normal distribution. However, because the number of systems is quite large (there are more than 50 systems in the data collection), using a multivariate normal distribution is impractical. Moreover, due to this large number of systems, the Bonferroni method will produce non-informative interval estimates. Therefore, the study settled for approximating the reliability for the whole automated BIM process by assuming that errors in different systems happen independently. Thus, by letting R denote the reliability of the automated BIM process:

$$R = \prod_{i=1}^{I} R_i, \quad (7)$$

where I is the total number of systems. Note that this analysis extends to any building type by properly defining systems for each building type and using the aforementioned procedure.

4.2 Preliminary Data

A pilot survey was developed for two reasons: (1) to determine if construction companies were able to share the data we needed for the statistical model and (2) collect some sample project data to use in the proof-of-concept. Contacted companies were also explained the concept behind the reliability model and asked to comment on their perception of its potential usefulness and utility.

The survey focused on the variables needed for the data model and also included questions like: "What was the type/style of this project?"; "What state was this project located in?"; "What was the approximate cost of construction for this project?"; "Who modeled the BIM model for this project?"; and "On this project, which, if any, part(s) of the BIM model had the most errors?". These questions were selected to help categorize and identify trends in the data as well as clarify details of the project types to use in future analysis.

After completing the general questions, participants are asked to identify which systems were modeled on the project. Systems included in the survey were selected based on UniFormat categories and limited to those systems found in a typical commercial building (Table 1).

After selecting systems that were modeled on the project, the survey asks participants to provide the BIM Model Percent Accurate, Percent of Project Cost, Percent Quantity Error Acceptable, and general comments for each selected system.

Surveys were sent to 36 companies who knowingly utilize BIM in some form to manage their construction projects. Of these 36 invitees, 13 responded to the survey. Of these 13, only 4 completed the survey with data. Of the 9 who did not complete the survey it was commonly noted that they did not currently use BIM for quantity take-off and estimating or did not keep track of the data types needed in the survey.

4.3 Proof-of-Concept Example

Table 2 shows a proof-of-concept of the reliability model that was developed within Excel using the statistical framework previously described. The complete model would include unit numbers for all components as listed in Table 1, only D2000 through D5000 were utilized in this example. Data for building 1 and 2 were received from two different contractors. Both of which were educational buildings. The rest of the data were filled in as examples of potential data to provide a proof-of-concept as to how the reliability model works and how someone would interact with it.

Table 2 Proof-of-Concept Reliability Model

Unit Number		D2000.00 - Plumbing		D3000.00 - HVAC		D4000.00 - Fire Protection		D5000.00 - Electrical	
% Error Tolerance (averaged) --->		5		5		5		7	
		Unit weight (%	Error (%)	Unit weight (%	Error (%)	Unit weight (%	Error (%)	Unit weight (%	Error (%)
Building 1	100,000,000	8	2	20	2	2	4	15	4
Building 2	80,000,000	9	30	25	30	3	5	12	30
Building 3	95,000,000	7	10	20	5	2	4	10	6
Building 4	150,000,000	6	15	30	6	4	10	11	9
Building 5	75,000,000	7	4	18	4	1	4	10	4
Building 6	55,000,000	8	5	15	3	2	1	8	2
Building 7	82,500,000	9	2	28	2	2	1	15	3
Building 8	91,000,000	5	0	30	10	1	5	12	5
Building 9	62,750,000	8	5	15	4	1	1	10	7
Building 10	71,500,000	7	10	20	15	2	1	9	7
Unit Reliability			0.330456761		0.325055405		0.497413142		0.416404779
Total reliability	0.022248718								

Within the reliability model, the user is able to look at only the components of the model that are within the building. To remove the other components from the model, they can simply input a "1" under that component in Unit Reliability. This will then calculate the total reliability based on only the systems that are within the building. If there are components of the model that the user is not worried about having accurate numbers or is not responsible for they can remove those from the equation by simply changing the unit reliability to "1". Meaning it will not be calculated.

The intent is that the user will use the model to identify those components of the model having the lowest reliability number (closest to "0"). These are the ones that, based on historical data, have the highest risk. Risk being defined as a combination of financial impact of an error and likelihood of an error. For instance, in the example in Table 2, HVAC has the lowest reliability number meaning it has the largest impact out of the identified systems on the success of the project. What the user would then need to do is review the HVAC portion of the BIM model and randomly check for accuracy. When the user is confident that the HVAC portion of the BIM model is correct, they can switch the "Unit Reliability" to 1, again adjusting the calculations. The process of checking components will continue until the "Total Reliability" is close enough to 1 that the user has confidence in the overall accuracy and is willing to take the risk in using the model for automated processes.

Confidence cannot be numerically defined within the model; however, qualitative data will be collected and tracked by way of comments when historical data is collected to see where most of the errors are reported. For instance, in the example data we were able to retrieve, one of the major comments was the wall types were not drawn to the appropriate thickness, if this was common for multiple projects it might be one thing that is suggested to be checked. This information will be developed as a supplement to the model.

5 Future Research

During the survey process and follow-up discussions with 6 of the firms that were invited to participate and only partially completed the survey, it is worth noting that all firms viewed the concept of the reliability model as very promising. Each firm acknowledged that trusting the automated results of a model that is created by another person or group is a problem because the firms are ultimately liable for the numbers being produced. This is the reason many of them do not utilize BIM for quantity take-off and estimating. They agreed that if the reliability model were implemented it has potential to give them more confidence in the models after quickly checking some systems. To this end, the research project will continue by identifying and working with industry partners to collect historical data. Initially, data collection will focus on a single building type and few industry partners. Since the companies who were able to supply actual data did so with education market sector projects, this will likely be the type of project used to collect preliminary data. After the data are collected they will be applied to pilot test the proposed reliability model in a more complete setting and also allow the companies to then test the model on new and upcoming projects to see if it helps them gain confidence in the building model.

Once pilot tested, a larger database system will be developed that can be populated with historical data from all types of projects. This can then add layers of information and different buildings with different systems to the original framework allowing for a more robust system. With a large enough data pool other variables can be added to the model, such as what part of the country the project is being built. Variables such as who the original creator of the model was will also be examined to see that has any influence to the historical accuracy trends. Other supplementary data can be included, such as where do most errors within the system take place to identify trends and key issues that users might want to check within the system.

6 Conclusion

The advantages and challenges of BIM, and its significant impacts on the AEC industry have been well documented. The current paper addresses one particular challenge in the use of BIM, namely calculation of material quantities; however, this research also addresses larger questions on the use of BIM and other automated tools in the AEC industry. How can design and construction professionals effectively utilize computer algorithms that are increasingly separating them from their traditional work tasks? What skillsets and methodologies will be needed by designers to evaluate and responsibly apply the results of automated processes? Answers to these questions will have profound implications on the state-of-practice of design and constructions professionals as information technology continues to advance and evolve within the AEC industry.

One particular application envisioned for the proposed framework is evaluation of results from automated multidiscipline design optimization (MDO). In one case study, MDO was demonstrated as a means of optimizing a classroom building for structural and energy performance (Flager et al 2009). MDO and other similar processes may require structural and mechanical engineers to evaluate the validity of automated results that they did not exclusively produce. It is also possible that they will be tasked with evaluating results that they had no hand in generating. This situation is similar to the focus of the current paper, wherein contractors are seeking to utilize BIM models created by other parties.

With the development of the reliability model, a tool is offered to AEC professionals to assist them in rationally conducting efficient, but responsible, reviews of automated results from models. This systematic review of the models can help cut down on risk of using models developed by other individuals for information the professional is ultimately responsible for. When the user is able to gain a higher level of confidence in the model they are using for automated processes, the more likely they will utilize that model to its full extent. This research hopes to help remove the stigma of using building models for automated processes and help AEC professionals gain confidence in the results. When utilizing the model then to create estimates or perform structural analysis, it can end up saving time and money for the job, a situation that can make all stakeholders happy.

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