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Applications of Building Information Modeling for High Performance Homes

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ABSTRACT: Building Information Modelling (BIM) has been applied to various stages in the life cycle of building projects, with a focus expanding from more traditional design towards areas of construction and facility management. This paper describes work exploring a suite of BIM technologies and IT tools that can help achieve the cost, time and quality targets during the construction phase of high performance single family house. The paper highlights the potential benefits that can be achieved through this BIM suite. The tools and technologies include the use of BIM for pre-fabrication, BIM for energy modelling, combining BIM and social media for knowledge management, BIM for 4D scheduling, integration of BIM and GIS to support facility management and generating as-built 3D models during construction. The proposed tool suite was applied during the construction of a prototype high-performance, low-cost single family home built on the campus of The University of British Columbia. The main goals of the construction project were to provide affordable and energy efficient housing to First Nations communities in Canada. The paper then explains the use of each of these tools on the project and the associated time and effort required for their implementation. The paper concludes by highlighting the extent to which the use of these tools helped the project achieve its goals and the envisioned benefits. An attempt is made to present a Return on Investment (ROI) on the use of the proposed suite of BIM technologies.

1 INTRODUCTION

1.1 *Introduction*

Building Information Modeling (BIM) is causing a paradigm shift in the Architecture, Engineering and Construction (AEC) industry, transforming the way buildings are designed, constructed and managed. BIM is moving the construction process from “lonely” to “social” data, in the sense that BIM is enabling project stakeholders to easily share digital project information with each other (ARCHIBUS 2009). This enables better design and management of the projects (in terms of cost, time and quality), and results in improved decision making.

While the potential range of BIM application areas is very broad, common usage is currently much more limited. BIM has most frequently been reported in the context of relatively large, complex, and high-budget projects and it is most often used for specific design and geometric clash-detection applications. Yet BIM use is gradually expanding to different project phases from pre-construction to facility management because of the advancing level of software and tools, growing industry experience, increasing numbers of people with BIM skills, and established libraries of BIM elements that can cut the modelling time and effort.

Meanwhile, the demand for energy-efficient and affordable housing has also been steadily rising worldwide. The use of BIM on such projects can potentially contribute towards achieving their goals by promoting a collaborative work process amongst project stakeholders, allowing architects to simulate building performance, optimizing schedule, and providing access to rich information to facility managers. This paper focusses only on small, single family housing projects, and explores how the use of BIM can benefit these projects.

The authors propose a suite of BIM technologies and IT tools that can be used during the construction phase of single family house. The underlying hypothesis is that this suite can facilitate achieving the cost, time and quality targets for an energy efficient, single family home. In order to test this hypothesis, the proposed suite was used during the construction phase of the AYO Smart Home Project - a pilot single family home built on the campus of The University of British Columbia (UBC).

This paper describes the combination of six different studies which were conducted on the AYO Project. Each study tested the use of a specific BIM related tool or technology on the case study project. The first section introduces the topic and the research hypothesis. The second section provides a background of the project and data collection techniques used. The third section summarizes the background, methodology and observations for each of the six studies. Finally, the fourth section concludes with the major findings and learnings from each study.

2 AYO SMART HOME: BACKGROUND AND CONTEXT

AYO Smart Home is a company based in Vancouver, Canada founded in 2015. Their goal is to provide First Nation communities and other markets with affordable, durable, and culturally appropriate housing while maintaining high levels of livability and energy efficiency. To help reach this goal, they have built a pilot home on the UBC campus as a research platform to optimize the construction of future homes. This home was used as a case study to test the proposed suite of BIM technologies. The design for the home was finalized in August 2015, construction started in September 2015, and substantial completion was achieved by January 2016. The two story, 1620 sq.ft demonstration home uses Magnesium Oxide (MgO) Structural Insulated Panel (SIP). In addition to the high- performance SIP panel envelope, the home uses innovative mechanical and lighting systems while adopting a passive design approach to maximize solar energy (AYO Smart Home 2015)

For data collection, the authors were provided complete access to the construction phase of the building, including 2D design drawings, other project documents, interviews with project stakeholders and access to site. Authors also had access to time-lapsed videos and site photographs.

3 IDENTIFYING AND APPLYING A BIM SUITE OF TOOLS AND TECHNOLOGIES ON AYO SMART HOME PROJECT

3.1 *Pre-fabrication using BIM*

The importance of using pre-fabrication in smaller scale projects–such as the AYO Smart Home Project–lies primarily on the ability to reduce the construction process times and eliminate design errors. These pre-made elements can lead to significant time and cost savings. The budget on smaller projects tend to be smaller and more restrictive. Hence, mitigation in case of errors or unanticipated events can hinder the completion of the project.

Pre-fabrication requires accurate information to minimize re-work. Hence, there is a strong case that BIM tools be used whenever prefabrication opportunities are available. Additionally, due to the computing power of these tools, multiple iterations can be considered in short amounts of time to determine the most cost effective and sustainable prefabrication layouts.

In this study, one of the authors, who is moderately proficient with AutoDesk Revit, made a Level-of-Detail 400 (architectural and structural) model using the 2D architectural and structural drawings provided by the project design team. Among the observations made:

- There were numerous discrepancies between various 2D drawings in terms of placement of multiple structural elements that, if left unnoticed, would result in rework and material waste on site. Using a BIM model, these were identified early.
- Using built-in Revit functionalities, the various module sizes could have been optimized to be less variant, which would drive down the risks of poor fit or using the wrong panel for the wrong place (a lack of panel uniformity was found to be a major hindrance to the construction productivity).
- Using the model, very accurate, almost shop drawing-like drawings could be produced, which could help ensure that the translation of information from the designer to the prefab wall suppliers was error free.
- More ambitious designs could be attempted since any possible clashes could be identified early-on.

3.2 *Energy Modeling using BIM*

As concern about the environmental impacts of building grow, private and public organizations increasingly require the building industry to design and construct buildings with minimal environmental impact(Azhar et al. 2009). Thus, more accurate energy estimation methods are required to anticipate the eventual operating energy consumption during the design phase. Many researchers have worked to develop more precise methods, and BIM is being adopted broadly as part of this trend. According to the recent studies, BIM-based energy analysis is considered to be useful for energy assessment of buildings (Aksamija 2012; Che et al. 2010; Dowsett and Harty 2013; Laine and Karola 2007).The greatest benefit reported is that changes to the design are reflected directly through BIM model, and the results of the energy analysis can be viewed immediately. As a result, more design iterations can be evaluated to improve efficiency and meet sustainability goals (Kalavagunta et al. 2015).

In this study, the BIM model was created and modified using Autodesk Revit. Energy simulation was conducted by Green Building Studio, which was connected to Revit. Simulations were done for 65 scenarios by varying the window size, position and orientation of the model. The methodology is shown in Figure 1

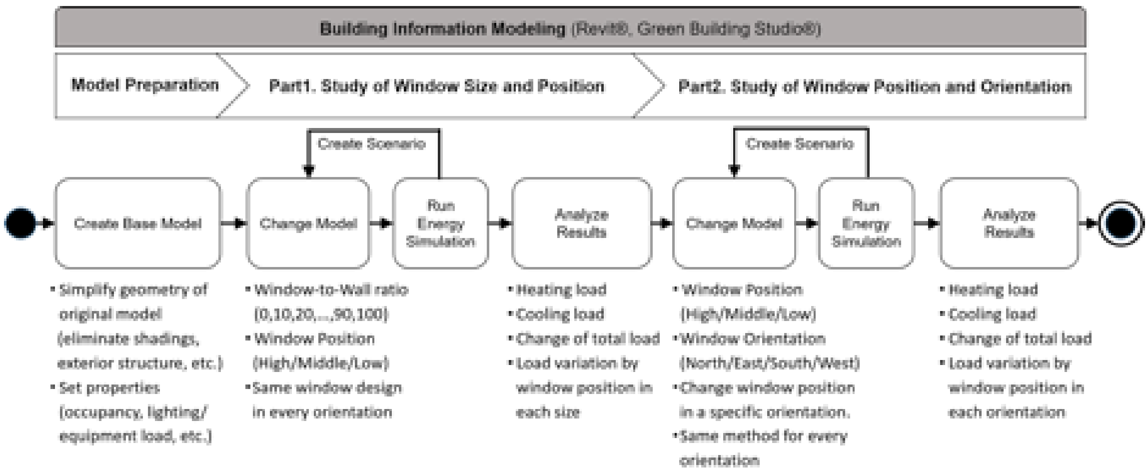

Figure 1 Research Methodology for Energy Modelling

In order to analyze the impact of window design on building energy load, the energy load of a single family house with different scenarios was estimated using BIM and energy analysis. Window size, position, and orientation were changed in 65 scenarios, and the heating and cooling load of each scenario was analyzed. First, the size and position of the windows were changed in

29 scenarios. The window-to-wall ratio (WWR) was changed from 0 to 100 percentages, and the position of windows moves from low to high. The energy simulation result showed that the annual energy load increased as the window size increased, raising by 45% as the WWR goes from 0% to 100%. The load variation by the window position in each size indicated that the window position had a negligible impact on energy load of less than 1%. In the next stage, the window position of each orientation of the building was changed in 36 scenarios to see what combination of window position yields the lowest energy load and which side of windows' position has the biggest impact on the energy load. Again, the differences were found to be very small, with the lowest energy load arising when all the windows were located at a middle height and the largest variations occurring when the windows were on the east side.

3.3 *4D scheduling using BIM*

This study involved assessing the usefulness of a 4D BIM model with respect to construction productivity. A 4D schedule was generated for the project using Navisworks by linking the 3D BIM model to the construction schedule. The information and potential productivity problems, which can be identified and enhanced through 4D BIM simulation, were analyzed. The framework used to implement BIM, adopted from Staub-French and Khanzode (2007) along with the time spent on each step is shown in Table 1 The times given are higher than expected norms since this was the first encounter of the student with using Revit, MS Project, and Synchro software.

Table 1 Framework to implement BIM

Development Stage	Effort in Hours
Step 1; Establish Installation Sequence	50
Step 2: Reorganize 3D Models	55
Step 3: Refine Schedule	10
Step 4: Link 3D Objects and Activities	13
Step 5: Refine 4D Model	0
Total Hours Spent	**128**

3.4 *Knowledge Management Using BIM and Social Media*

Knowledge is one of an organization's most important assets, hence organizations should strive to capture and reuse the knowledge of their workers to support continuous improvements. The construction industry is often associated with low levels of productivity, one reasons for which is poor knowledge management since mistakes are past projects are frequently repeated. In addition to BIM, social media platforms are another recent invention that have diverse applications in every field, including construction. The main objective of this study was to assess the usefulness of a BIM-based social platform for knowledge management (particularly for tacit knowledge) in the construction industry.

In this study, a SocioBIM platform called "Green 2.0" (CANARIE 2015)was used to facilitate knowledge management on the project. The Green 2.0 platform allows users to walk through a BIM model, comment on particular elements, categorize their comments, and reply to comments by others. Hence, it was selected for implementation on the prototype house project to assess the potential for BIM-based knowledge management during construction.

Installing the pre-fabricated SIP panels was selected as an appropriate activity for implementing the platform. The installation lasted for approximately 14 days. The challenges, issues or successes relating to productivity and site safety were documented on a daily basis by conducting semi-structured interviews with stakeholders, recording time lapse videos, and observing on-site operations. Five project team members were interviewed: the Project Manager, the Architect, the Site Superintendent, the Structural Engineer, and the Panel Installer.

An experiment simulated these central project participants using the prototype daily (since it was not possible to impose the system on the actual participants in real time during construction).

Once the panel installation was complete, five research participants (graduate students at UBC who were also involved in studying the construction phase of this project and were, therefore, very familiar with the details of the construction operation) were assigned one of the 5 aforementioned roles. The architectural BIM model of the project was uploaded on the system (using IFC format) and shared with the participants. The participants were then directed by the platform administrators to walk through the BIM model and discuss the various issues related to specific elements on the platform. This exercise lasted for 14 days, the same duration as the installation of the panels. On each day of this exercise, the participants were shown the recorded time-lapse video of panel installation on the actual day of construction. They were also orally briefed on what activities took place on-site and what challenges and successes happened on the actual day of construction. The key observations made from this experiment are discussed in section 4.4.

3.5 *Integrating BIM and GIS*

Since life-cycle operation and maintenance cost more than initial construction, BIM is increasingly being of interest as a potential approach for effective building facility management. With collaboration of mechanical, electrical and plumping system data, facility managers can obtain rich and reliable information from BIM to manage facility management process. Many past research projects have been conducted in this area (Arayici et al. 2012; Becerik-Gerber et al. 2012; Sabol 2008) At a larger scale such as campuses, however, both building-level and campus-level data are required to fulfil an operation. Taking campus service as an example, when the operational office receives a request to fix the air- condition in a particular building, the personnel need the campus map to locate the building and find the correspondent service zone and its service manager. He or she also needs the interior building map to find the equipment room; furthermore, detailed information about the air-condition equipment is required. In such cases, BIM is very limited for locating an element accurately, providing surrounding landscape information, and conducting spatial queries, etc. (Rich and Davis 2010). Therefore, BIM approaches need to be extended to increase the efficiency and accuracy of facility management process. One potential discipline that could be incorporated is Geographic Information System (GIS).

GIS can represent and analyze real-world objects and their relationships, typically at the community level. It supports rich spatial data storage and organization. GIS has matured in managing a large number of facility assets (Rich and Davis 2010). BIM can be extended with GIS so that it can visualize campus-level information and support spatial analysis such as generating routes to a target location, in addition to building scale data. Hence, combining BIM and GIS technology to realize building data and geospatial data sharing and exchange has much potential value in facility maintenance.

The Industry foundation classes (IFC) standard is an open schema that supports BIM data sharing and representation (buildingSMART.org). The IFC standard can contain information of a building's whole lifecycle, from design, through construction, to operation and maintenance. CityGML is an open data and XML-based GIS data format for storing and exchanging city models. The ArcGIS 3D City Information Model (3DCIM) is an information model that works well for data management, analysis and visualization. They both represent virtual 3D urban objects. This study explored a way of converting IFC to CityGML, and finally moving the data model to a GIS environment for visualization. Due to similar data structure of IFC and CityGML file, integrating IFC and CityGML is a potential solution to enhance interoperability between BIM and GIS data. As 3DCIM performs better on managing data, CityGML is converted to 3DICIM for FM purpose. This is achieved by two-step transformation: 1) IFC to CityGML; 2) CityGML to 3DCIM. Safe Software can provide both reader and writer tools for manipulating these data formats with its product Feature Manipulation Engine (FME); therefore, FME is used to take care of technical aspects of the conversion process.

The main contribution of this study is the development of work processes to integrate building data and its community into geospatial context to better support FM operations. The methodology of converting IFC –> CityGML –> 3DCIM consists of four stages. First, capture major building model feature classes from IFC standards. Second, create mapping schema between IFC classes and CityGML classes and develop a FME workbench. Third, create the workbench using existing feature relationships between CityGML and 3DCIM. Fourth, conduct the actual transformation for the target project and deploy the result in CityEngine to visualize the data.

The proposed approach was demonstrated using the BIM model of the AYO smart home and the UBC campus map. The UBC map was originally in CityGM, Level-of-detail 1, which means it only shows extruded building footprints on campus. The AYO BIM architectural model was used to generate an IFC model. The two models were imported into workbench separately for transformation and merged into one 3DCIM database finally. The database was exported to Esri CityEngine product for visualization. The detailed family house model and simplified campus buildings were then merged together. Data manager could easily search and edit building attributes in the software. The lessons learned from this implementation are described in section 4.5.

3.6 *Using Project Tango for Quality Assessment*

Assessing the quality of construction for compliance with the design intent has been a challenging task in the AEC industry. As modern design methods using BIM) techniques have been increasingly adopted by the AEC industry, construction quality assessment using BIM has become a challenging new task for practitioners. In the past few years, 3D as-built models for construction quality assessment have been developed using data acquisition techniques like 3D laser scanning and photogrammetry. However, certain limitations such as high cost, high expertise requirements, and time-consuming processes restrict their usage for construction quality control.

The main objective of this work was to study the applicability of using a new, affordable, easy-to-use, and faster modeling technology to produce 3D as-built models for facilitating the construction quality control process. Specifically, Project Tango by google—a low-cost, hand-held tablet device that can capture 3D spatial models from real objects and spaces by using advanced vision, depth sensor, and image processing tools—was tested on the AYO Smart Home to assess its suitability for such projects. Three different scenarios (including interior and exterior environments such as footings and interior rooms) were modelled using Project Tango.

Project Tango relies on various device applications that assist in developing the requiring as-built models. Two mobile applications were found to be useful for model-generation purposes: (1) Tango Constructor; (2) Room Scanner (Google Developers 2015).Tango Constructor generates a 3D meshed object directly that can then be exported to .obj format (Google Developers 2015)while Room Scanner generates a 3D point cloud with a storage limit of up to 500,000 points. The data acquisition limitations, file storage format, and post processing software availability for the exported files from these applications were studied to identify the most suitable data collection tools.

A post-processing method was developed to prepare the scanned as-built models for comparison with the design BIM. These accuracy level of these as-built models was also evaluated using dimension accuracy analysis. The prepared as-built models and the design BIM were then integrated and adjusted in the Autodesk Navisworks environment to perform the quality control assessment. This assessment process includes object completeness testing and spatial deviation analyses.

4 DISCUSSION AND CONCLUSIONS

4.1 *Pre-fabrication using BIM*

The model mentioned in section 3.1 was a product of roughly 35 hours of work, done by one person with an average knowledge of the tool (not inclusive of the time to be educated about the tool). It is estimated that this time could have been reduced by at least one half with a more experienced operator, resulting in a relatively small time investment to produce the prefabrication BIM model. Examining the final result of the project and comparing the cost of rework and requests for information, which cause many project delays, can suggest the relative benefit-cost value of these model. On this basis, particularly given the repetitive nature of this project and potential for future reuse, the authors believe this approach to provide a positive benefit-cost value.

As the use of both prefabrication and BIM expands, individual project teams will need to decide whether to apply these technologies on their projects. Some of the relevant considerations in arriving at this decision include the following:

- Might the project be repeated elsewhere?
- Are there risky design decisions involved?
- Does the client want a unique and customized product?
- What are the local availability of necessary resources?
- Are there sustainability goals?
- What is the availability of proficient BIM modelers?
- Are most activities in the schedule on the critical path?
- What is the contingency funds for the project?

It is by close examinations of these and other similar questions that the true benefit/cost value of using these systems (BIM and prefabrication) in conjunction are revealed and the project managers and owners can decide on a suitable solution.

4.2 *Energy Modeling using BIM*

As this study was based on a small-scale building, the total energy load was relatively small, so the energy load variation arising from different window configurations was insignificant in terms of annual energy costs. For larger buildings, the impact of window size on energy costs could be significant, although window position and orientation would still have very small impacts. Testing with measurements from actual window installations would be very beneficial to validate these results. It would not be practical to physically test the many scenarios examined through energy modeling here, and these modeling results could be beneficial in identifying the best configurations to use for physical testing.

Visual comfort and other considerations of window configuration were neglected in this research. Lighting load was also not considered since the required lighting load was relatively small in the original design, but if the building scale changes and users require more lighting, the lighting load should be considered. Finally, this research assumed that the energy modeling was accurate in resolving the impact of the various window configurations.

4.3 *4D scheduling using BIM*

The 4D model was reviewed by the project superintendent, who was sked to consider the expected impact of using the model for planning and for reviewing with sub-contractors. The superintendent estimated that a significant number of change orders and requests for information would take place earlier in the project, during design and construction planning rather than during the main construction phase. He expected that this would lead to cost and time saved during construction. The results of this project, then, were that 4D BIM scheduling is useful for such projects and can improve construction productivity.

4.4 *Knowledge Management Using BIM and Social Media*

Once the implementation was complete, a total of 44 comments were created by the participants, and 24 of these were replies to other comments. A few key observations regarding the use of the platform can be made:

- The 3D BIM model in the platform made the discussions more holistic and engaging as the visualization made it easy to identify conflicts between different building elements and to anticipate future risks related to delays, safety, or other issues. For example, one discussion highlighted that the installation of the front posts and the roof could have been accelerated if certain modifications were made on the concrete footing in advance.
- The problem solving followed a collaborative approach and there was continuous feedback

from different participants. This can ultimately result in creating a continuously evolving knowledge base of best practices that can be used in future projects

In addition to these observations, some recommendations were made by the participants to improve the platform functionality and to make it more engaging for users:

- Have the option of tagging different participants, quoting comments from others, and rating the solutions of others.
- Add an ability to select multiple building elements at once to assign group comments. Include an ability to search for keywords within the comments.
- Add multimedia content to the comments.
- Provide a structured format for comments.

In conclusion, the authors of this study believe that such platforms can potentially benefit homes similar to AYO Smart Home, since the lessons learnt from one project can effectively be applied on subsequent future projects due to similar design and construction methods involved.

4.5 *Integrating BIM and GIS*

Despite the fact that Esri product supports lossless CityGML transformation, the authors still found that there were some elements missing during the conversion process. One such case was missing exterior columns in the 3DCIM. This is mainly caused by misclassified elements when converting IFC to CityGML. Sometimes, elements in IFC are not correctly assigned to the expected feature class, and some errors happen in the FME workbench. From another perspective, this approach required a high qualified BIM model, any minor mistakes in original building model may cause conversion fault. Additionally, although both CityGML and 3DCIM support features other than building, such as streets and trees, in this study, the author only considered the building asset and its components as research objects. Other type of elements like roads and surrounding landscapes were not included.

In conclusion, it was observed that the BIM and GIS integration allows the facility managers to view both campus level data and detailed building model in the same scene and easily search and edit object attributes in the CityEngine or other GIS products. It can also improve the efficiency of searching and viewing data during maintenance operations and highly reduce dependency on experienced personnel and paper documents.

4.6 *Using Project Tango for Quality Assessment*

The results of the construction quality assessment highlight that the Project Tango device's use of reflected IR light made depth perception difficult in certain cases, such as modeling black surfaces and window regions. Furthermore, the results show that the accuracy of the as-built models created with the device were generally accurate but had dimension errors of up to 6% (or sometimes more for small components). The Project Tango device sometimes failed to record elements of smaller dimension accurately. Major disparities are found in certain windows location, and object completeness testing identified several missing objects from the initial design model, thus assisting the team in recognizing the design changes that occurred during the construction phase.

In addition, based on the experience from this work, an analysis was conducted in order to provide a better overview about the advantages and weak points of the Project Tango in comparison with the two other common techniques. Detailed results of this analysis are summarized in Table 3 which is developed based on different related works (Bhatla et al. 2012; Mahdjoubi et al. 2015; Volk et al. 2014; Zhu and Brilakis 2009). This table includes three following categories: (1) cost involved; (2) data acquisition accuracy; and (3) user convenience. The analysis shows that Project Tango can act as a viable option for generating the as- built models depending on project requirements. For projects with a budget constraint or small scale projects where it is not necessary to develop highly accurate models, this analysis highlights that Project Tango has the potential to serves as an alternative to 3D laser scanning. In addition, Project Tango seems to be suitable solution in projects where it is intended to quickly generate models without special expertise instead of opting for Photogrammetry. However, the level of dimensional accuracy may limit its potential for quality control applications. Although the resulting models were very usable, most of the modeling process was still manual. Thus there is a demand for developing automated methods to address this issue and to reduce the potential human errors in stages like data collection, post-processing, and quality assessment.

Table 2 Comparison of different techniques used for as built model generation

Category	Parameters	3D Laser Scanning	Photogrammetry	Project Tango
Costs involved	1. Equipment Costs	Highly costly in the range of $50K-$150K	Affordable in the range of $500-$1000	Affordable with a price tag of $500
	2. Software support and costs	Need expensive proprietary software	Need software like Autodesk 123D	Need open source software like Meshlab
User convenience	1. Post processing time requirement	Huge amounts of time required	Time required is more than that of laser scanning	Time required is less
	2. Mobility	Not very mobile	Highly mobile	Highly mobile
	3. Learning Curve	Very steep learning curve	Minimal learning curve	Minimal learning curve
Device accuracy and suitability	1. Acquisition, Accuracy, Cost	High accuracy and range to the extent of a millimeter	Moderate accuracy and loses focus for large distances	Moderate accuracy compared to laser scans
	2. Weather conditions	Not affected by weather conditions much	Highly affected by weather like cloudy situations	Highly affected by weather like sunlight

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