Using Scan-to-BIM Techniques to Find Optimal Modeling Effort; A Methodology for Adaptive Reuse Projects

M. Esnaashary Esfahani[a], E. Eray[a], S. Chuo[a], M.M. Sharif[a], C. Haas[a]

[a]Department of Civil and Environmental Engineering, University of Waterloo, Canada

E-mail: mesnaash@uwaterloo.ca;

Abstract –

With increased computing power to render 3D models and affordability of as-built data acquisition technologies, new techniques for enhancing the quality of pre-project planning of adaptive reuse projects can be investigated. The main objective of this research is to present a decision making methodology to select the optimum effort using 3D as-built point clouds to develop a BIM of an existing building. Three value proposition and risk reduction areas are investigated: (1) dimensional, (2) material, and (3) disassembly. To measure the cost and value of developing models with corresponding value propositions, a small case study is conducted. Three different Model Detail Levels (MDL) are defined for adaptive reuse projects, and corresponding models are developed for each of them. The value of each model is considered based on its ability to provide information about dimension, materials, and fixtures within an existing building. The cost of the scan-to-BIM process includes costs of purchasing 3D acquisition device, buying BIM modeling software license, scanning and registration, and developing BIM using scan-to-BIM techniques.

Keywords –

Adaptive Reuse; Value of Information; Pre-project Planning; Scan-to-BIM; Modeling; Existing Buildings

1 Introduction

Having a successful project or receiving the best outcome from a project has always been a goal of engineers and project managers. In general, a project is successful when it meets all of its goals and expectations and when all of the stakeholders (e.g. owners, consultants, contractors, suppliers, end-users, community, etc.) achieve their requirements individually and collectively [1]. The Construction Industry Institute (CII) conducted extensive research and concluded that improving the planning process during the early stages of a project lifecycle would be more effective and cheaper in order to improve a project's outcome, as opposed to later stages [2]. Planning during the early stages of a project life cycle is called pre-project planning and is defined as, "the process of sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project" [3]. Pre-project planning would be more effective and ensures higher probability of having successful design, construction, and operation phases, depending on the efforts that have been dedicated to completely define the details of a project's scope [4]. Scope definition is considered as defining the vague and uncertain areas such as area and site investigation, existing brownfields, weather conditions, safety and security regulations that will be used during the detailed design, construction, and operation phases.

Gathering information is the first step of defining details of a project's scope. There are several pre-project planning tools that help a project team (owners, engineers, architects, contractors, investors, and developers) to know which type of information is needed. However, there is not any clear decision making methodology regarding the process and prioritization of information gathering. The methods and technologies to obtain information, the cost and value of each method, the amount of risk reduction, and finally the optimal amount of information are the steps that must be addressed through further research.

The objective of the adaptive reuse approach is revitalizing old and obsolete buildings and returning them to the use cycle. Therefore, as-built condition of an existing building is one of the most important information categories for defining project scope of an adaptive reuse project. However, obtaining useful as-built dimensions of an old existing building can be costly. Typically, either as-built drawings are not available, or they might be inaccurate [5]. Lack of updated as-built drawings brings more uncertainty to the adaptive reuse projects that causes financial loss and time delay during design and construction phases. Thus, it is necessary to provide updated as-built information during pre-project planning and before authorizing a project for the detailed design and construction phase.

Using 2D surveying tools and software is the common way to create as-built drawings of an existing building [6]. However, there are drawbacks associated with this method of as-built data collection, such as high level of error, long time of surveying, difficulties of obtaining details of building’s fixtures and facilities, difficulties of converting the 2D surveying information to the 2D drawings, and complexity of interpreting the 2D drawings. On the other hand, usage of advanced software and technologies that have 3D surveying and drawing capabilities can support the process of developing more exact and less complex as-built drawings. In addition, 3D as-built drawings can provide more information regarding the existing conditions of a building to the project team.

The objective of this paper is to fill the mentioned knowledge gap by presenting a decision making methodology for finding the optimal amount of effort in the data collection and modeling step in adaptive reuse projects. This methodology will be presented by conducting a case study to select the optimum effort required in the 3D data acquisition step (laser scanning and structured lighting has been utilized) and to develop a 3D as-built BIM (Building Information Model – defined and described in more detail in section 2.5 of this paper) of an existing building. The method, which has been used in this case study to obtain as-built information, can be generalized to find the optimal amount of information about other project scope elements.

2 Literature review

2.1 Adaptive Reuse

There are numerous definitions for “adaptive reuse” in the literature. In this research, adaptive reuse is accepted as the process of extending the useful life of a historic, old, obsolete, and derelict building, considering new usage compatible with historic background, new socio-cultural demands, political and environmental regulations of a building’s location and applicable building codes, maximizing the reuse and retention of existing structures and fabrics, and improving financial performance and economic viability of buildings [7], [8]. Since adaptive reuse specially deals with old and historic building restoration, UNESCO defines it as a respectful process to the form, character, structure, and historic integrity of buildings, while finding an appropriate use for them [9].

Extending building useful lives, preserving natural resources, reducing waste production, controlling negative impacts of old buildings, satisfying new demands, and preserving cultural, historical and social aspects of a building are among the most important key drivers of the adaptive reuse approach [10]. Hence, adaptive reuse is a novel sustainable approach to fulfill previously mentioned key drivers.

2.2 Uncertainty and Information

In the project management literature, uncertainty is used as a general concept and is defined as the degree of deviation between actual outcomes of an event from its predicted outcomes. In fact, uncertainty is the effect of lack of knowledge and information about an event. There is an inverse relationship between information and uncertainty level [11]. Providing more information increases the knowledge of the project team about the project and consequently enhances the project predictability and decreases its uncertainty. Although providing more information has the mentioned values, it also adds to the cost of the project. Thus, there is a practical limit to the amount of information needed to reach a reasonable level of uncertainty. As long as the marginal expected value of working with more information (lower uncertainty) is positive, and the cumulative expected value of working with more information is higher than the expected value of working without any information (higher uncertainty), it is reasonable to collect information and reduce uncertainty.

In other words, collecting information more than this limit will decrease the net value, because after the limit point, the rate of information gathering cost would be higher than value enhancement. This limit will differ from scope element to scope element and project to project. So, it is up to the project team to come up with the limit of information for each scope element according to the specific project. Or, where information is fuzzy, applying the 80:20 rule works well, and here we identify ways of prioritizing so that rule can be observed.

2.3 LOD and Other Methods

The project design phase involves an iterative process in which the final product is achieved after several changes and improvements. In construction projects, be it a new project or an adaptive reuse project, design progress starts with conceptual drawings, and a fully coordinated construction model is created after many iterations. While design evolves from conceptual drawing to ready for construction model, details of the model elements and model disciplines become more mature and accurate. In this iterative process determining the detail level of the design is a complicated problem. In the literature there are several frameworks proposed to determine the detail levels of the model elements and model disciplines. One of the known frameworks that focuses on design details of the model elements is the Level of Detail (LOD) framework.

The LOD framework is created in 2005 by VICO Software Ltd. to track cost estimates of the projects, and later it was adopted by the American Institute of Architects (AIA). After AIA improved the LOD framework into specific levels, the meaning of the LOD acronym was changed to “Level of Development”, and in 2008 the definition of different LOD levels were released. AIA defined five LOD levels (LOD 100, LOD 200, LOD 300, LOD 400, and LOD 500) for model elements in a Building Information Model. According to the “AIAE202-2008 BIM Protocol Exhibit” contract document, LOD 100 refers to the conceptual drawing of a model element which shows its area, height, volume, and location, while LOD 500 means that the model element has reached its as-built version, and it would include useful information for operations and facility management phases of a project [12]. However, it is important to note that, there is no defined total LOD or LOD of the whole model. LOD definitions are created for single model elements on a design model [13]. Figure 1 represents five different LOD versions of a steel framing column model element according to the BIM Forum’s 2018 LOD Specifications [14].

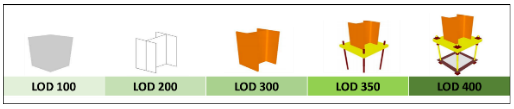

Figure 1. Representation of different LOD Levels of Steel Framing Column (Source: [14])

CII’s Model Maturity Index (MMI) definitions are an example of a framework that can be used for determining the design detail level of a design model and design progress by focusing on information added to the related model disciplines [15]. In 2017, CII published a new set of definitions that is called MMI, and a toolkit called Model Maturity Risk Index to measure modelling progress and productivity in building projects. CII provided these definitions and related tool for 12 disciplines including; Piping, Structural, Instrumentation, HVAC, Equipment, Civil, Electrical, Fire Protection, Layout, Foundations, Buildings, and P&IDs in building type of projects. Defined MMI levels follow similar sequence with LOD levels. There are seven different MMI levels for each modeling discipline varying between Generic Model to Facility Management information added as-built model. Similar to LOD, there is no such total MMI of whole model, these definitions are developed for disciplines in the model.

Inspired by the concepts of LOD and MMI, the Model Definition Level (MDL) is defined in this study to emphasize that there are different effort levels regarding the scan-to-BIM process, which may lead to different value levels.

2.4 3D Acquisition

2.4.1 Laser Scanning

Three-dimensional laser scanning named LiDAR (Laser Detection and Ranging) has been introduced and used in industry since the 1970s as an advanced imaging technology. Due to the high cost and low reliability of the early devices, this technology did not spread widely until the 1990s [16]. Several technologies, such as computer, optics, and micro-chip lasers came together to form the laser scanner as a high-tech device. Laser scanners can be used to capture the geometry of a construction site accurately and quickly [17]. The output of a 3D laser scanner is a dense point cloud for which each point has three coordinate indices “X”, “Y” and “Z” based on the scanner’s coordinate system. In fact, the laser scanner records the 3D geometry of objects by collecting thousands or millions of points located on the objects’ surfaces.

To this date, many researchers have worked on using laser scanners for tracking new construction and fabrication processes, and developing as-built models of construction sites [18]. However, there is limited research about exploiting the capabilities of laser scanner to record 3D as-built of existing buildings and collect some mandatory information to feed the design and construction of adaptive reuse projects [19]–[21].

2.4.2 Structured Lighting

A structured-light 3D scanner is a device for measuring the three-dimensional shape of an object using projected light patterns (infrared light in Microsoft Kinect and Structure IO) and a camera system [6]. The projector projects speckle patterns on the objects and the sensor calculates the distance of a point to itself. In order to use triangulation, two separate images must be captured. In terms of accuracy, the support group of Structure IO (one of the commercially available scanners, which uses structured light technology) claims that the device can achieve an accuracy of 1% of distance measured. While the accuracy of structured-lighting scanners is significantly lower than laser scanners, the ease of use and acceptable accuracy for small objects has made them an acceptable option for rudimentary modeling efforts.

2.5 Building Information Modeling (BIM)

According to international standards, Building Information Modeling (BIM) is defined as “shared digital representation of physical and functional characteristics of any built object, which forms a reliable basis for decisions” [22]. Predecessors of BIM were used for product modeling, and had wide application in the petrochemical, automotive, and shipbuilding industries [23]. BIM can be categorized as having a narrow to broad perspective, based on its capability and the amount of information contained. Narrow perspective may include 3D (building model), 4D (3D plus construction schedule), and 5D (4D plus cost calculation) models of a building. On the other hand, BIM with broad perspective goes further and considers the energy and environmental performance of a building. As a matter of fact, the narrow and broad perspectives refer to technical and functional issues of a building, respectively [19].

Until recent years, the use of BIM had been restricted to new construction and earlier stages of the building's lifecycle [19]. However, as BIM enables project teams to precisely manage the building's information along the whole lifecycle [24], it is able to support later stages of life cycle as well. Therefore, BIM can be used to manage maintenance, renovation, deconstruction, adaptive reuse, and the stage of building end of life [25].

Although using BIM for existing buildings has many benefits, such as providing valuable as-built documentation and planning renovation or retrofit projects, research studies have indicated infrequent implementation of BIM for existing buildings. The need for high modeling efforts in order to convert collected data to a BIM, handling uncertain data and objects, and difficulties in updating the BIM of existing buildings have been the main obstacles of implementing BIM for existing buildings [19]. Thus it is valuable to focus on implementation of BIM for existing buildings and research further into this field.

3 Research Methodology

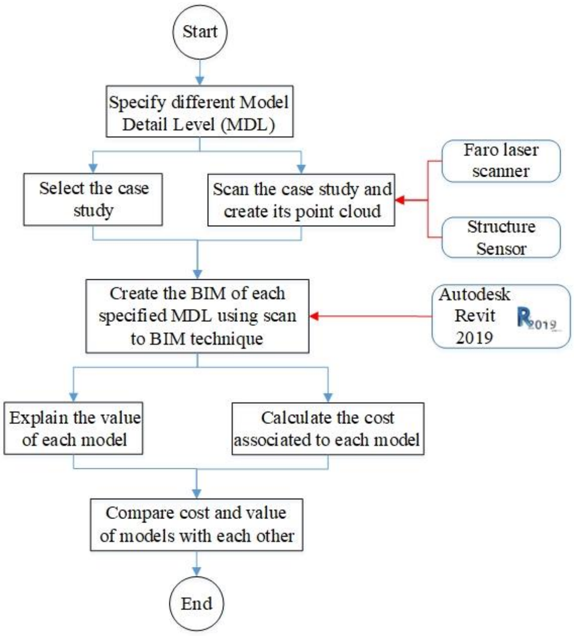

Figure 2. The overview of research methodology

3.1 Model Detail Level (MDL)

3.1.1 Value of Dimensional Information

Collecting dimensions of all physical surrounding is necessary for re-designing a space, whether in renovation or adaptive reuse projects. Furthermore, to optimize the effort required, designers try to minimize the amount of effort required in the disassembly and gutting steps (try to reuse space as much as possible). An important aspect of having a BIM of a project is instantaneous access to all dimensions, such as location of the openings (windows, doors, etc.), location of the elevators and stairs, and the area of spaces in an existing building. On projects where no prior model exists (or they are not accurate) using scan-to-BIM methods can be effective to rebuild an accurate model. As such, having access to the dimensional information resulted from the scan-to-BIM effort is considered as one of the axioms to determine how much effort shall be designated for the process. Access to dimensional information is referred to as "Dimension" and is the only existing value of information provided by MDL 1 models.

3.1.2 Value of Material Information

In addition to the dimensions, it is essential to consider the materials that have been used in an existing building for selecting the most compatible new usage with the prior one. Also, adaptive reuse seeks to fulfil the requirements of environmental sustainability. This goal will be achieved by maximizing the use of existing buildings' materials through recycling, reusing and minimizing the need for new materials. Decreasing the rate of natural resources depletion, greenhouse gas emission, and global warming effects due to lower demand for material production and transportation are benefits of using existing materials. Hence, "Material" of each component is another important type of information that must be considered for designing the adaptive reuse projects.

3.1.3 Value of Disassembly Information

In order to increase the efficiency of recycling and reusing processes, the project team needs to access more detailed information than a building's dimensions and material. Examples of detailed information include the routes of plumbing and wiring networks, location and details of electrical and mechanical facilities, location of sprinklers and smoke detection facilities, type and location of lighting, and location of a building's fixtures and furniture. These kinds of information are called "Disassembly" information, because they will help the project team to efficiently plan for disassembly, recycling and reuse the existing materials.

In this study, the LOD and MMI concepts are utilised, and a new framework that is related to the detail of a whole design model is defined. This new framework is called Model Definition Level (MDL) and divided to three different levels based on the provided information. A BIM satisfies the requirements of MDL 1 (Dimension information) if contains the dimensional information about an existing building. The BIM will be upgraded from MDL 1 to MDL 2 (Material information) by adding material information of building's components to the model. In addition, adding disassembly information to a BIM that already satisfies the requirements of MDL 2, will upgrade this to MDL 3.

3.2 Case Study

The case study of this conference paper is the Ralph Haas Infrastructure and Sensing Analysis Laboratory, located within Engineering 3 building at the University of Waterloo.

Figure 3. The panorama picture of the case study

The objective is to develop a BIM for each specified MDL by converting the 3D point cloud of the laboratory to the BIM (scan-to-BIM technique). Two different devices including the "Faro Focus M70" laser scanner and the "Structure Sensor" (Structure IO) are used to capture the point cloud. The Faro laser scanner is a professional scanner that can capture up to 488,000 points per second. Its measurement range is between 0.6 and 70 meter, and the ranging error is 3 millimeters. Furthermore, capturing HDR pictures and applying color information to the point cloud is another advantage of laser scanners, which can be useful in the scan-to-BIM process. On the other hand, the Structure Sensor is a structured light scanner which is mounted on Apple iPad. By incorporating an IMU (inertial motion unit) and elements of SLAM (simultaneous localization and modeling), it does real-time registration and does not need manual registration to create the point cloud. Thus, the scanning process is significantly faster when Structure Sensor is used for scanning. Furthermore, the scan registration process using laser scanners requires sophisticated knowledge in post processing software.

Figure 4. Point cloud: Structure IO (left) and Faro (right)

3.3 Developed Models

The captured point clouds are used to develop BIM for each specified MDL. As seen in Figure 4, the captured point cloud using the Structure Sensor does not have enough information (point density, precision and accuracy) to recognize the openings and details of the building fixtures. Therefore, it is only feasible to use it to attain the first MDL (which only contains dimensional values). So, MDL 1 is developed using both point clouds, while MDL 2 and MDL 3 are developed based on the point cloud obtained by the laser scanner.

3.3.1 MDL 1

As explained in section 3.1.1, the first MDL includes only the overall dimensions of the building. The walls, floor, ceiling, windows, and doors are modeled to fulfill the requirements of this MDL. Elements are in the generic state and no material properties are assigned to them. Figure 5 shows the developed BIM model for this MDL using the Structure Sensor and Faro point cloud. Modeling the doors and windows was only feasible based on the Faro's point cloud.

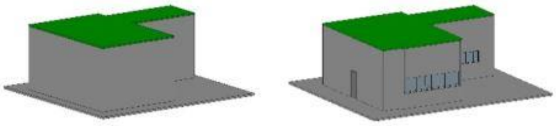

Figure 5. Developed BIM model based on Structure Sensor (left) and Faro (right)

Since a point cloud is a set of discrete points, the placement of a building's elements in the model depends somewhat on the modeller's judgment. Hence, a model's dimensions will be different for the same objects, which are modeled by different modellers. So, to investigate the effect of modellers on the dimensions of BIMs, six different modellers developed the BIMs for the first MDL, using the Structure Sensor and Faro point cloud. The wall height, floor area, and floor perimeter were extracted from each model and the mean value and standard deviation were calculated. According to the Table 1 the coefficient of variation differs from 0.84% to 3.52%, which may seem like a low value, but it is an unacceptable amount of error in absolute dimensions (up to 20 cm) from an engineering design perspective. It may be acceptable from a building operation or maintenance perspective. So, it can be observed, pending more sophisticated experiments and statistical analysis, that inconsistency between different modellers has a more significant effect on error than the type of scanner used in this case.

To compare the accuracy of the Faro laser scanner and the Structure Sensor, the true dimensions of the laboratory are measured by a laser meter. The "wall height", "floor area", and "floor perimeter" are calculated by using the true dimensions, and they are equal to 4.78m, 81.07m^2, and 44.41m, respectively. Also, the error range associated to these parameters are calculated by comparing their true values with the extracted data from the developed models. Figure 6 shows the error percentage range associated to Faro and Structure Sensor. According to this figure, the Structure Sensor dramatically underestimates the dimensions, especially for area and perimeter. On the other hand, the Faro results is closer to the true dimensions, which emphasizes its superior accuracy than Structure Sensor. The error range depends on the modeller's precision during the scan-to-BIM process. The maximum and minimum error range is related to wall height and floor perimeter modeled by Structure Sensor's point cloud, respectively. The error range associated to wall height modeled by the Structure Sensor's point cloud is higher than Faro. While the error range associated to each of the floor perimeter and the floor area is similar for Structure Sensor and Faro.

3.3.2 MDL 2

To develop the second MDL, material information is assigned to elements of the case study. The type of material is retrieved from the Faro point cloud and observations from the project's site. Also, the exact thickness of exterior walls is calculated by comparing the point cloud of the case study from inside and outside view.

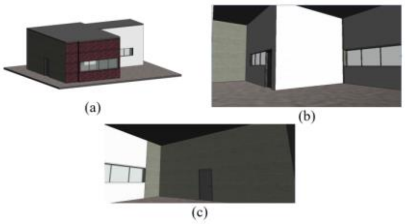

Figure 7. (a) Allocated materials to outside walls (brick cladding, concrete block, dry wall system)-(b) and (c) Allocated materials to inside walls and floor (dry wall system, concrete block, and carpet)

Table 1. The effect of having different modellers on the wall height

	Wall Height (m)		Floor Area (m^2)		Floor Perimeter (m)	
	Structure Sensor (m)	Faro Focus (m)	Structure Sensor (m^2)	Faro Focus (m^2)	Structure Sensor (m)	Faro Focus (m)
Modeller1	4.70	4.83	73.62	78.70	42.6	44
Modeller 2	4.40	4.70	76.21	81.09	42.8	44.40
Modeller 3	4.70	4.80	74.8	80.5	42.5	44.32
Modeller 4	4.90	4.90	74.70	81.5	42.7	44.6
Modeller 5	4.78	4.78	75.30	80.71	42.9	44.4
Modeller 6	4.72	4.88	70.09	75.32	41.9	43.2
Mean	4.70	4.81	74.12	79.64	42.57	44.15
Std. dev.	0.165	0.072	2.147	2.323	0.356	0.506
COV	0.0352	0.0150	0.0290	0.0292	0.0084	0.0115

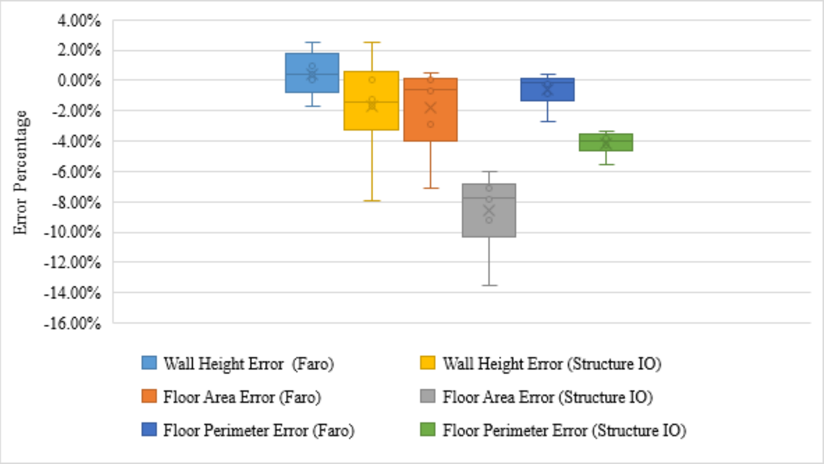

Figure 6. Error percentage ranges associated to Faro and Structure Sensor (Structure IO)

3.3.3 MDL 3

In this level, detail of plumbing, wiring network, HVAC system, and building fixtures and furniture, including their materials, are added to the BIM.

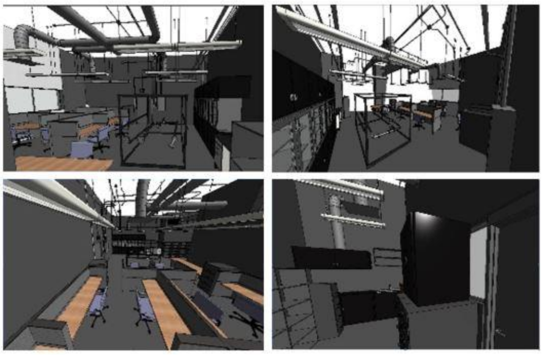

Figure 8. Developed BIM for MDL 3 based on Faro point cloud

3.4 Costs and Benefits

The cost of the scan-to-BIM process includes cost of purchasing a 3D acquisition device, license of BIM software, scanning and registering, and developing the BIM using scan-to-BIM techniques. The average renting cost of Faro M70 is CDN$650 per day. There is no renting option for Structure Sensor and it must be bought at the price of CDN$500. Also, the monthly price of an Autodesk Revit license is CDN$365.

To calculate the cost of scanning and registration, as well as developing the BIM, CDN$100 per hour is considered as the wage of an expert person. The time of completing each activity is multiplied by this wage and the outcome is the cost.

Table 4: The detail of cost calculation

Model Definition Level	MDL1	MDL1	MDL2	MDL3
Type of Scanner	Structure Sensor	Faro	Faro	Faro
3D Acquisition Device	500	650	650	650
BIM Software License	365	365	365	365
Scanning & Registration	17	200	200	200
Scan-to-BIM	33	33	67	2000
Total Cost (CDN$)	915	1248	1282	3215

4 Discussion

The cost of the scan-to-BIM process would increase as the BIM model becomes more detailed. Therefore, it depends on the needs, available budget, and project team's judgment to select which MDL is the most valuable for a project. If the project team is involved in finding a new usage for reviving a building, which is a high level of planning, an approximate estimation of buildings' dimensions might be sufficient for them. In this case, it makes sense to use Structure Sensor and MDL1, which has the lowest cost. At the end, the cost of this alternative would be lower than CDN$915, because of the salvage value of Structure Sensor (it can be sold as a second handed device).

On the other hand, selecting MDL3 will bring more value to an adaptive reuse project if the project involves detailed planning. The cost of this MDL is CDN$3,215. The capability of having exact time and cost estimation, material quantity estimation, disassembly plan, recycle and reuse plan, and design of electrical and mechanical facilities are several values that are provided by MDL3.

When the new usage was selected, and the project team is involved in high level of architectural design (e.g. assigning different spaces to different applications), the planning level is between the two-mentioned boundary level. In this case, MDL1 with Faro, or MDL2 makes more sense and provide both more value and sufficient information to the project.

5 Conclusion and Future Work

Based on the results of this research, the significance of the added value would be different from project to project and it is up to project team to decide which amount of information is optimal.

For the future plan, it is valuable to consider the losses associated to the lack of information in the planning levels and compare this to the cost of developing BIM for each MDL to make a decision in such a way that has the least cost and provides highest value to a project.

References

[1] B. V. Sanvido, A. Member, F. Grobler, K. Parfitt, M. Guvenis, and M. Coyle, “Critical Success Factor For Construction Projects,” *Engineering*, vol. 118, no. 1, pp. 94–111, 1992.

[2] U. of Texas at Austin. Construction Industry Institute, G. E. Gibson, and R. Haggard, *Pre-project planning: Beginning a project the right way*. Institute, University of Texas at Austin, 1994.

[3] C. I. I. (CII)., “Pre-project planning handbook.”

Univ. of Texas at Austin Austin, Tex., 1995.

[4] C.-S. Cho and G. E. Gibson, Jr., “Development of a Project Definition Rating Index (PDRI) for General Building Projects,” *Constr. Congr. VI*, pp. 343–352, 2000.

[5] B. Becerik-Gerber, F. Jazizadeh, N. Li, and G. Calis, “Application areas and data requirements for BIM-enabled facilities management,” *J. Constr. Eng. Manag.*, vol. 138, no. 3, pp. 431–442, 2011.

[6] B. Furht and S. Ahson, “Handbook of Mobile broadcasting DVB--H,” *DMB, ISDB-T MEDIAFLO, 1st Ed. USA Taylor Fr. Gr.*, pp. 67–73, 2008.

[7] C. Langston, F. K. W. Wong, E. C. M. Hui, and L. Y. Shen, “Strategic assessment of building adaptive reuse opportunities in Hong Kong,” *Build. Environ.*, vol. 43, no. 10, pp. 1709–1718, 2008.

[8] S. Conejos, C. Langston, and J. Smith, “Improving the implementation of adaptive reuse strategies for historic buildings,” p. 11, 2011.

[9] E. Sugden, “The adaptive reuse of industrial heritage buildings: A multiple case studies approach,” University of Waterloo, 2017.

[10] K. Dyson, J. Matthews, and P. E. D. Love, “Critical success factors of adapting heritage buildings: an exploratory study,” *Built Environ. Proj. Asset Manag.*, vol. 6, no. 1, pp. 44–57, 2016.

[11] K. Samset, “Project management in a high-uncertainty situation,” no. May, 1998.

[12] U. S. AIA, “Document E202TM-2008 Building Information Modeling Protocol Exhibit,” *Am. Inst. Archit.*, 2008.

[13] C. Boton, S. Kubicki, and G. Halin, “The challenge of level of development in 4D/BIM simulation across AEC project lifecyle. A case study,” *Procedia Eng.*, vol. 123, pp. 59–67, 2015.

[14] BIM Forum, “Level of Development Specification For Building Information Models and Data,” 2018. [Online]. Available: https://bimforum.org/wp-content/uploads/2018/09/BIMForum-LOD-2018_Spec-Part-1_and_Guide_2018-09.pdf.

[15] CII Reseach Team no. 332, “Measuring Progress and Defining Productivity Metrics in Model-based Engineering.,” 2017.

[16] Y. Turkan, F. Bosche, C. T. Haas, and R. Haas, “Automated progress tracking using 4D schedule and 3D sensing technologies,” *Autom. Constr.*, vol. 22, pp. 414–421, 2012.

[17] G. S. Cheok, S. Leigh, and A. Rukhin, “Calibration experiments of a Laser Scanner,” *NASA STI/Recon Tech. Rep. N*, vol. 2, 2002.

[18] M. Nahangi and C. T. Haas, “Automated 3D compliance checking in pipe spool fabrication,” *Adv. Eng. Informatics*, vol. 28, no. 4, pp. 360–369, 2014.

[19] R. Volk, J. Stengel, and F. Schultmann, “Building Information Modeling (BIM) for existing buildings - Literature review and future needs,” *Autom. Constr.*, vol. 38, pp. 109–127, 2014.

[20] J. Jung *et al.*, “Automation in Construction Productive modeling for development of as-built BIM of existing indoor structures,” *Autom. Constr.*, vol. 42, pp. 68–77, 2014.

[21] A. Akbarnezhad, K. C. G. Ong, and L. R. Chandra, “Automation in Construction Economic and environmental assessment of deconstruction strategies using building information modeling,” *Autom. Constr.*, vol. 37, pp. 131–144, 2014.

[22] I. S. O. Standard, “ISO 29481-1: 2010 (E), Building Information Modeling Information Delivery Manual Part 1: Methodology and Format (2010),” *Google Sch.*

[23] J. Wong and J. Yang, “Research and application of building information modelling (BIM) in the architecture, engineering and construction (AEC) industry: a review and direction for future research,” in *Proceedings of the 6th international conference on innovation in architecture, engineering & construction (AEC)*, 2010, vol. 1, pp. 356–365.

[24] X. Liu, M. Eybpoosh, and B. Akinci, “Developing as-built building information model using construction process history captured by a laser scanner and a camera,” in *Construction Research Congress 2012: Construction Challenges in a Flat World*, 2012, pp. 1232–1241.

[25] J. C. P. Cheng and L. Y. H. Ma, “A BIM-based system for demolition and renovation waste quantification and planning,” in *Proceedings of the 14th International Conference on computing in Civil and Building Engineering (ICCCBE 2012)*, 2012.