BIM Implementation for Conventional On-Site and Off-Site Manufacturing Construction

By

Beda Barkokebas

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Department of Civil and Environmental Engineering
University of Alberta

ABSTRACT
Collaboration among project participants is key to the success of construction projects. When project information is not efficiently communicated or easily shared among project stakeholders, such conditions often lead to cost overruns and schedule delays. Particularly, this phenomenon can frequently be observed and further be augmented for industrialized constructive methods such as modular construction because changes in an execution phase are not typically allowed after the production process has begun. Although the efficiency of Building Information Modelling (BIM) applications have been proven in processes such as drafting, 3D modelling, and quantity takeoff, practices to increase collaboration and a knowledge-sharing environment have been slow to develop. This research proposes a framework to integrate stakeholder information and workflow by applying the (i^3) concept (information, intelligence and innovation) and using tools such as ontology to comprehend the current process and adapt documents which have already been provided, such as cost estimations and construction drawings, using the BIM model as a database in which data is added, shared, and utilized for future processes beyond design purposes. Two case studies are presented in this thesis. In the first case study, the proposed framework is applied to a modular residential project in order to investigate the level of detail required, and automate the cost estimation process while liking the BIM model to the simulation model of the manufacturing production line in order to estimate labour cost based on distributions, thereby quantifying the uncertainties of the construction process as well as opportunities to enhance the workflow between the design, Project Management Office (PMO), and manufacturing departments during the design and manufacturing stages. Furthermore, as presented in the second case study, this framework is adapted to assist general contractors during the coordination and tendering phases of a multi-storey building.

“One step further and you are no longer at the same place”
Chico Science

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CHAPTER 1 INTRODUCTION

1.1 Motivation

In order to remain competitive, several contractors are shifting to industrialized construction methods, which include the transition of many activities to a controlled (off-site) environment from the traditional on-site practice. Han et al. (2011) attribute the recent advances in off-site construction to benefits such as increased quality and productivity, and improved safety practices. Moghadam et al. (2012a) indicate that building industrialization requires special methods in its development, particularly in the design criteria, due to its manufacturing requirements for design and drafting. In fact, the product development for off-site construction relies on multiple disciplines which require different levels of detail; also, a major collaboration between stakeholders is necessary in order to remain competitive in regard to cost in comparison to the current stick-built practice. Deficiencies in the process, such as the communication between design and production, lead to even greater levels of rework and budget overruns in industrialized construction methods (e.g., modular, panelized, and precast). In the case of modular, modules are built in an efficient, controlled environment and are then assembled on-site, introducing concepts which originated from the manufacturing industry such as the production line and component pre-assembly. Moghadam (2014) indicates, in this case, the link between design and production is essential, since once the construction of the module is initiated, changes in the design are far more costly than the current stick-built practice, and there is a high level of variability between each client's demands for customization. In the pursuit of improving efficiency in this area, Building Information Modelling (BIM) is recognized as a suitable platform to promote the exchange of information while providing an effective visualization of the project's virtual prototype (Goh et al., 2014).

Parametric three-dimensional models, known as BIM models, have been widely implemented by construction practitioners in recent years in order to automate processes and increase collaboration among stakeholders in construction projects. Although BIM was developed in the late 1970s by mechanical and aerospace design teams, the AEC (Architectural, Engineering, and Construction) industry only began adopting this tool recently due to the high cost of licensing and overwhelming computer processing in the past (Eastman et al., 2011). McGraw-Hill (2012) indicates the engagement of AEC companies toward the use of BIM in recent years, forecasting that 94% of the industry intends to make a serious commitment to BIM (McGraw-Hill Construction, 2012). According to the same study, Canada experienced a 46% increase in the adoption of BIM from 2009 to 2012, proving the efficiency of this tool through its rapid adoption by the industry.

Although the efficiency of BIM tools has been proven in several processes, including drafting, 3D modelling, and quantity takeoff (Liu et al., 2015a; Zhao, 2015; Succar, 2009), practices to support the increase of collaboration and a knowledge-sharing environment have been slow to develop despite the usage of BIM having doubled since 2007 (McGraw-Hill Construction *apud* Neff et al., 2010). Miettinen and Paavola (2014) acknowledge the use of BIM as a realistic method to increase organizational integration, although this requires a deep understating of the real problems associated with BIM implementation. One of the most common problems is determining the level of detail to be delivered from the model versus the accuracy of the information that needs to be acquired, and quantifying this tradeoff. In the case of modular construction, this gap proves to be wider due to the deficit of available tools able to provide accurate shop drawings and detailed quantity takeoffs. Liu et al. (2015a) state that BIM has not yet achieved its potential in construction prefabrication, due in part to the fact that parametric models, which are still roughly modelled by architects and engineers, do not meet the criteria for modular construction practitioners. In fact, despite the several data required to successfully coordinate a construction project (drawings, specifications, cost, etc.), BIM is a suitable tool to store and distribute the information among stakeholders provided a defined framework is in place to inform and guide all parties involved.

Developed at the University of Alberta, the (i^3) concept provides a clear directive in order to organize and address different information to provide solutions for all involved. This is a threefold concept in which the information (i^1) is added to the system under predetermined intelligence (i^2) in order for the system to provide innovation (i^3) as per the user requirements. By applying the (i^3) concept, this research proposes a framework to enhance the workflow and productivity of modular contractors by addressing the specific needs of modular, including the ability to front-load the BIM model with information from various stakeholders without compromising the planning process or the automation of non value-added activities such as quantity takeoff. Moreover, the scope of the framework is adapted more broadly within the construction industry by applying it to a general contractor's multi-storey residential building project.

Although it bears remarkable advantages, limitations of BIM are addressed in this research in regard to the challenges of implementation and cost estimation. This research presents a comprehensive literature review outlining the barriers in the implementation of BIM, putting both technical and cultural barriers on an equal level, thus comprehending the introduction and use of this technology as a paradigm shift, and not limited to an exchange of computational applications. Moreover, this research establishes a connection between the BIM model and simulation engines in order to acquire a realistic labour cost taking into consideration the inherent uncertainties of the construction process. Therefore, the research combines advantages from both applications (BIM and simulation), providing detailed material takeoffs to be connected with cost databases and simulation engines, and acquiring realistic durations for activities and labour cost from simulation models in order to acquire accurate and comprehensive cost estimations in a timely manner for a given project.

1.2 Research Objectives

This research is built upon the following hypothesis:

"Building information modelling (BIM) can be adapted to modular construction and general contracting and can automate the quantity takeoff process and improve inter-stakeholder workflow in a consistent manner from project to project."

This research aims to propose a framework which will enhance the workflow between the design, cost estimation, and manufacturing departments, and will automate activities such as quantity takeoff and reporting using BIM tools in order to assist modular contractors in their product development. The framework also incorporates information, which is currently employed by the manufacturing industry, into the estimation process of panel construction and assembly by front-loading the BIM model with pertinent data. The objectives of the research are presented below:

- Evaluate various stakeholder needs in regard to the 3D model, and develop a set of requirements in order to produce the BIM model

- Obtain pertinent information and quantity takeoffs with a high level of automation consistently through different projects
- Adapt the proposed framework for bids and general contracting while maintaining the level of automation applied in the original framework

1.3 Thesis Organization

Chapter 1 (Introduction) describes the research motivation, its objectives, and an overview of the study.

Chapter 2 (Literature Review) provides a description of the different stages of construction design, cost estimation, and metrics to evaluate the level of detail in each stage, as well as a summary of previous studies regarding BIM-based cost estimation.

Chapter 3 (Methodology) describes the development of the proposed framework by front-loading the BIM model with information regarding various stakeholder requirements.

Chapter 4 (Case Study) demonstrates an application of the framework and its current limitations.

Chapter 5 (Conclusion) summarizes the research contribution, its limitations, and suggestions for future work.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

In this section, a general discussion about the (i^3) concept, data exchange and integration within the construction industry, as well as of building information modelling (BIM), cost estimation, and off-site construction, is presented.

2.2 The (i^3) concept: Information, Intelligence and Innovation

In order to accommodate all stakeholders' requirements and manage all information, the implementation of this framework relies on (i^3), an active concept developed at the University of Alberta, which stands for information (i^1), intelligence (i^2), and innovation (i^3). This approach dictates that once information is processed and intelligence is added, the resulting byproduct of the first two components applied to the process is innovation. This study shall be a result of the combination of information from different stakeholders, hence bridging the communication gap in this industry. According to Manrique (2009), a large portion of information is expected to be connected to the 3D model during the design and planning phases, thus making an approach based on the (i^3) concept relevant to integration that is required to approach this research problem. Therefore, this concept is suitable for this study, which intends to connect various types of information by front-loading the BIM model with intelligence in order to automate the estimation and planning processes for off-site construction.

2.3 Integration and data exchange in the construction industry

A construction project requires substantial collaboration among a significant range of agents due to the diversity of specialties involved regardless of project size. Managers, engineers, designers, and other professions at the lowest technical level establish a communication framework on different hierarchical levels in order to receive and distribute information from multiple sources Mutis and Issa (2012). Within the construction domain, poor performance in terms of project delivery is often observed due to recurrent cost and schedule overruns. Evbuomwan and Anumba *apud* Baiden et al. (2006) partially attribute this to the lack of collaboration among project participants. Other factors include the high number of small companies in the market and poor flow of information (Alashwal and Fong 2015). Focada et al. (2013) state that, despite its strong presence in society, the construction industry relies on the manual input of knowledge from several agents with a notorious level of completion between companies and the constant increase of sophisticated demands from clients. In fact, Schöttle and Gehbauer (2012) state that the active environment, coupled with the asymmetry of data exchanged by different stakeholders, leads to unclear information.

The problem that surrounds information sharing in construction is recognized in several areas, including safety, project management, and product development. Ulang et al. (2010) consider the construction industry as a highly fragmented environment where the lack of knowledge is a primary reason for a high accident rate, which causes cost and time overruns. Fang et al. (2010) attribute several accidents in the industry to nonstandard knowledge, ambiguous information, and failure in sharing reasons that caused the accident. In order to overcome this problem, Xiaohua et al. (2015) relate positive results by using social networks in order to promote a platform for clear communication and improved safety performance in construction trades. Alsamadani et a. (2013) apply social network analysis to identify communication patterns between small construction trades and measure their performance accordingly. Le et al. (2014) apply ontology into a similar network in order to solve issues such as ambiguity of terms used by different parties when sharing information about safety. In fact, the use of social networks to enhance communication and knowledge sharing is current industry practice. Ling and Li (2012) make use of this tool in order to evaluate project management techniques and its respective success from different players in order to evaluate performance and implement better practices in future projects.

Despite recent advancements in technology and communication methods, the construction industry continues to lag behind other sectors (Klinc et al., 2010). Many construction companies still rely on traditional tools, such as e-mails, spreadsheets, and phone calls (Nourbakhsh et al., 2012), which do not synchronize/centralize all information pertaining to the project in a desirable manner, hence opportunities exist for miscommunications and informalities that can cause rework and delays. Although the construction industry has been aware of this issue for over two decades, the problem still exists (Dave et al., 2010). In fact, data feeding continues to be a problem in the industry making it difficult to communicate among the interested parties and predict results for future projects. Niknam and Karshenas (2015) recognize the challenge to integrate information in construction projects and propose the use of Semantic Web to automate the information process in cost estimation and improve the workflow between stakeholders in an attempt to centralize all information pertaining to a project in a manner that can be processed and used as a benchmark for future projects. Decision-makers and individuals are not capable of processing and synchronizing all the available information. Data is often produced and distributed in various formats such as drawings, Gantt charts, spreadsheets, etc., due to the various disciplines involved in a construction project. The fact that different parties tend to develop and update their own models, however, Browning (2014) underscores the danger of this practice, pointing out traditional overlapping of information, poorly synchronized and disparate information, assumptions, and concerns. The fragmentation described above begins at the early stages of a project, such as the design phase. The design phase is traditionally treated as a separate activity from the construction phase, which leads different teams to work toward their own objectives and often in conflict with each other (Anumba et al., 2002). A typical example of this phenomenon is the lack of interoperability of tools and deliverables between architects and engineers, which forces stakeholders to rely on individual expertise to interpret drawings and perform manual quantity takeoffs. This, in turn, often results in misinterpretation and errors in estimation and project coordination. Moghadam (2014) states that there is no single tool or application capable of producing all data for all project phases inclusively, and concludes that there is a need to better combine different sources to improve the data exchange process.

2.4 Building Information Modelling (BIM)

The concept of parametric modelling in construction has been discussed since the 1970s (Eastman, 1974); more recently, the concept has become known as building information modelling (BIM), a term introduced in the 1990s (van Nedervenn and Tolman, 1992). Although well-known for its 3D modelling functionality, BIM also offers a model capable of gathering information about the project with elements and features that have been specifically designed for the construction industry. Definitions of BIM have evolved extensively under various perspectives and that every author uses its definition for their own terms. In fact, there is no clear definition for BIM which has been widely adopted by professionals in industry or academia. BIM stands as a repository of information pertaining to different phases or the entire life cycle of a construction project, which may or may not be represented by 3D elements, and which is shaped and shared by a diversity of stakeholders. BIM represents a significant technological enhancement compared with traditional 2D computer-aided design (CAD) drawings in terms of graphics, data exchange, and collaboration. Eastman et al. (2011) underscore the considerable effort and time required to provide critical assessment as one of the most common problems when working with current 2D drawings; this method also introduces risks of error in important phases such as cost estimation and energy-use analysis, which are often performed last, and does not allow the opportunity to make important changes or undertake value engineering to address inconsistencies in the original design. Despite the clear advantages of BIM, the architecture, engineering, and construction (AEC) industry still struggles with the transition from CAD to BIM. Some barriers are addressed in Table 2.1 below, where they are categorized as either cultural or technical in nature.

Table 2.1 Main barriers for BIM implementation

Technical domain	Cultural domain
• Interoperability and exchange of data	• Training and human resources
• Best practice standards	• Culture change
• Legal aspects	• Definition of scope

The technical domain pertains to issues that can only be solved by technological advancements or actions from official organizations. Cheung et al. (2012) indicate that interoperability is the key aspect underlying the BIM concept, where a lack of interoperability creates barriers among stakeholders that hinder their ability to seamlessly work together on a model. Various software companies have been developing applications and have been criticized for the lack of interoperability among them (Jardim-Goncalves and Grilo, 2010). Despite advancements in the development of standards to ensure a stable exchange of information between different files, such as the Industry Foundation Classes (IFC), there is no completely reliable method or format that guarantees the integrity of data, thereby necessitating the interoperability of BIM files (de Andrade and Ruschel, 2010). Despite the recent intensive use in the industry, best practices such as the progression of the BIM model toward the development of a project still remain undefined for overall practitioners (Bedrick, 2008). Leite et al. (2011) indicate an eleven-fold increase in the modelling time from doubling the effort when reaching a superior level of detailing in BIM models for mechanical and electrical coordination. Monteiro et al. (2013) reach a similar conclusion, identifying a two-fold increase in the modelling time of structural elements with the addition of formwork.

In response to this, the American Institute of Architecture (AIA) has released the Level of Development (LOD), which classifies elements in the BIM model progressively in five stages (100 to 500). Later that same year, BIM Forum (2013) added an intermediate LOD in this classification between LOD 300 and 400, LOD 350, which enables the representation of a specific system with extra detailing but not enough information to address installation and assembly information. Table 2.2 demonstrates the minimum content requirements for each LOD and the authorized use for cost estimation according to AIA (2013) and BIM Forum (2013). A deficiency of this classification is that it prioritizes the geometry of the element rather than the information it contains. Nevertheless, this is the common metric used in North America, and it is thus employed in the present research to quantify the enhancements of the proposed framework.

Porwal and Hewage (2013) state that the use of BIM raises important legal issues such as contractual indemnities, copyright, and the use of documents not yet standardized by the industry. Despite the fact that legal documents and forms pertaining to these matters are being distributed throughout industry and academia (AIA, 2013), they are not being distributed and/or adopted at a suitable pace.

Table 2.2 Level of Development (LOD) classification and its authorized use for cost estimation (AIA 2013, adapted and BIM Forum (2013), adapted)

LOD	200	300	350	400	500
Characteristic	Approximate quantity, size, shape, location, and orientation	Specific quantity, size, shape, location, and orientation	Specific quantity, size, shape, location and orientation based on actual specifications	300 LOD and detailing, fabrication, assembly, and installation information	Verified model on file
Cost estimation	Estimate derived from approximated geometries and/or quantities	Suitable for procurement based on specific data	Suitable for procurement based on actual specifications	Based on actual cost of the element model	Not applicable

The cultural domain listed in Table 2.1 refers to issues related to culture change within the industry, specifically those which are dependent on a shift in current practice among individuals or small groups. Yan and Damian (2008) argue that the allocation of human resources for training and adapting the workflow regarding the use of BIM are the most latent barriers for the application of BIM in the AEC industry. Culture change constitutes a large barrier to any effort to bring innovation to a process, and the implementation of BIM is no exception. Li-Ren (2007) points to this resistance to innovative processes and technologies as an explanation for the fragmentation of the AEC industry. Due to the industry's limited knowledge of the actual capabilities of BIM, their expectations cannot be met without a proper scope to define the objectives and deliverables of BIM implementation. This research thus aims to address the challenges in the cultural domain through a framework that collaboratively addresses the defined needs of various stakeholders, taking into consideration both cultural and technical barriers.

2.5 Use of Ontology in BIM

The use of ontology is a recommended approach to pursue both technical and cultural barriers due to its capability to create a common ground for different stakeholders, develop an explicit level of communication, depict the relationships between these barriers, and address possible solutions. Noy and McGuiness (2001) define ontology as a formal and explicit description of relationships, properties, and concepts between different agents in a system. In fact, ontology provides a vocabulary that can be used to develop a domain in order to formally demonstrate the expectations and requirements for all stakeholders involved (Arvidsson and Flycht-Eriksson, 2008), thus adding transparency and reliability to the process as a whole. Ontology is applied to BIM in several cases such as construction defect management (Park et al., 2013), construction safety (Zhang et al., 2015), and cost estimation (Lee et al., 2014). Kreider (2013) develops an ontology to provide a shared vocabulary applied to BIM and enhance its use through the facility life-cycle. Liu et al. (2016) employ ontology to depict the relationship between framing and drywall elements within the BIM model, making them explicit for the engine, thus adding an extra layer of intelligence to the prototype and acquiring detailed estimations based on these relationships. In fact, the use of ontology has the potential to define and conceptualize the relationships between building elements, which prior to this were implicit in related documentation and personnel experience, through the BIM model thus allowing the engine to comprehend the design at the same level as construction practitioners.

Research aligned to this line of thought has been implemented and discussed. Kim and Grobler (2009) apply an ontological approach in order to check design compliance between the proposed drawings contained in the BIM model and its requirements regarding specifications and documentation produced as well as remediate inconsistencies through the project coordination process. Luo and Gong (2014) develop a BIM-based ontology for code and safety compliance in deep foundation construction plans in order to avoid mistakes or misunderstandings and automate the process for this portion of work. Regardless of the many applications found in the literature, many researchers apply ontology to BIM, taking into consideration one stakeholder who controls the entire process from beginning to end. This research proposes the application of a BIM-based ontology in order to depict the expectations, attend to the requirements, and improve the function of a collaborative workflow among multiple stakeholders. Moreover, this research intends to promote the use of ontology as a catalyst to address the needs of modular practitioners more clearly for construction planners and designers by naming the BIM elements of this framework and promoting the BIM model as a hub of information. In order to achieve this objective, the author demonstrates the elements used in this ontology in Table 2.3 below.

Table 2.3 Components of an Ontology

Ontology Component	Description
Class	A group or set sharing common attributes (Merriam- Webster, 2013)
Sub-class	A group or set inside a Class
Attribute	A feature or quality regarded as a characteristic or part of someone or something (Oxford Dictionary, 2013))

2.6 Cost estimation

Cost estimation is a fundamental output of a project which represents the necessary financial investment to accomplish it. The Project Management Institute (PMI) defines cost estimation as the quantitative assessment of the likely cost to complete a project, including all resources which may be presented in summary or detail (PMBOK, 2000). Cost estimation is performed and reviewed at different stages of a project, from its inception, to control, and completion. The accuracy of an estimate progresses according to the definition of the project from different documents such as designs, industry information, and commercial agreements. The Association for the Advancement of Cost Engineering International (AACE) has published five types of estimates that apply to construction, which are presented in Table 2.4 below. Table 2.4 depicts five different classes advancing from 5 to 1 (5 being the least level of detail and 1 being the most), representing the level of definition and usage, respectively. It is observed that the effort necessary to perform a cost estimation represents 0.005% to 0.5% of the total cost of a project, depending on the size of the project and its progress according to the current stage. It should be noted that classes of estimation may not be performed by a single entity. General contractors are capable of estimating their projects at Class 3; thus, during the tender process, trades will perform a Class 2 or 1 estimation and provide the final quotation for the bid depending on the tender documents.

Table 2.4 Estimate classes classification (AACE 2013, Adapted)

Estimate Class	Maturity Level of Project Definition (%) and final purpose of estimate
Class 5	0 to 2: Screening or feasibility
Class 4	1 to 15: Concept study of feasibility
Class 3	10 to 40: Budget authorization or control
Class 2	30 to 75: Control or bid/tender
Class 1	65 to 100: Check estimate or bid/tender

Quantity takeoff is a fundamental part of cost estimation and it is typically documented in a Bill of Quantities (BOQ). The current process of generating this document is time-consuming, error-prone, and heavily reliant upon interpretations by the professionals performing this task. Moreover, continual changes in the design reviews make the process of accurately updating the BOQ difficult to achieve due to the various factors involved such as design changes, trades involved, and decisions. The use of BIM is suggested to address this problem due to its parametric features and adaptation of tools to the construction industry. With the introduction of parametric modelling, schedule extraction has become a rudimentary task in programs such as Autodesk Revit, ARCHICAD, and Macrostation. However, these schedules are not suitable for cost estimation due to the lack of necessary detail. For the purpose of extracting a detailed BOQ, software such as Autodesk Quantity Takeoff, Innovaya, and Vico Software are used concurrently with previously mentioned BIM programs, providing a stable link between the 3D models in order to reproduce the impact of design changes in a timely manner. The estimation process is still not automatic, though, as the data extracted from the model must be verified in order to match the correct elements and price information, which, in many cases, an estimator must check manually in order to adjust any gaps in the assessment (Zhiliang et al., 2011).

Despite the technological advancements and availability of such solutions in the industry, these tools are not commonly used by practitioners. Monteiro and Martins (2013) identify the lack of a classification system as one of the major barriers in this regard due to the absence of standardization in the form of a Work Breakdown Structure (WBS), a tool used in industry to centralize all the specifications connected to the given BIM model. A WBS is composed of items at different levels and under codes according to a specific classification system. The best practice to automate the takeoff process is to link data from the BIM model to a code present in the WBS, thereby establishing a "bridge" between the parametric model and the cost estimation. There are several classification systems available in the AEC industry, such as MasterFormat, OmniClass, Uniformat, and UniClass. However, these do not consider the use of a BIM model for estimating purposes, and are based solely on the stick-built construction practice. Therefore, these classification systems are not suitable for the specific case company in this research, although they do provide a subject for further research.

2.7 Off-site construction manufacturing and simulation

The industrial revolution introduced a more productive supply chain, and also made an impact on many sectors of society, including the AEC industry. In this context, Crowley (1998) identifies three main principles in the industrialization of construction: (1) the standardization of building components; (2) the production and pre-fabrication of building components under controlled conditions; and (3) the coordination of building systems. The industrialization of construction represents a complete paradigm shift from traditional practice; rather than constructing components on-site, making the project susceptible to a range of factors which inhibit production, elements are built in a controlled environment. As an alternative, off-site construction manufacturing, a method in which the majority of building components are fabricated in factory conditions in order to be assembled on-site in a more timely manner, is gaining momentum in the AEC industry, resulting in more sustainable, safe, and cost-effective construction. The main investments to implement an off-site manufacturing plant are described in two parts: (1) the space and machines required to assemble the production line, and (2) the engineering team to monitor and perform the work (Al-Hussein, 2016). Part one—space and machines—is relatively inexpensive and, once bought, will be used for a significant portion of time despite the fact that part two—engineering team—requires constant training and support in both design and production areas. Thus, this research addresses two barriers for the implementation of off-site manufacturing: (1) the design and planning requirements for an efficient production line, and (2) a quantitative assessment of the production improvement brought forth by this new method.

Liu et al. (2015b) argue that industrialized construction methods should leverage the benefits of BIM tools, including the capability to assist owners in the design and planning phases, in order to achieve their full potential. In fact, off-site construction manufacturing demands a higher level of accuracy and detailing due to its characteristic of preassembly, which makes any on-site error far more costly than in the conventional stick-built system. Goulding et al. (2012) reinforce this by arguing that the automation of off-site activities, facilitated by BIM, represents an area of productivity growth, reducing uncertainty in the design and providing accurate information from the parametric model. Webster (2014) indicates that models produced by architects and engineers with a Level Of Development (LOD) equal or inferior to 300 are not suitable for manufacturers due to the lack of construction components (e.g., wall bracing, king studs, etc.) in the model. The extensive effort to acquire these models puts into question whether the output from this analysis adds true value to the overall process. Hence, a study mapping the requirements of the different stakeholders involved in the process is required to address this question.

Establishing a production and productivity benchmark is an important step when planning to implement and monitor an off-site construction manufacturing plant. According to Taghaddos et al., 2014, scheduling multiunit modular projects through commercial applications (e.g., Microsoft Project, Primavera, etc.) is not an effective process due to the quantity of constraints to be satisfied and allocation of resources (e.g., space, skilled crew, etc.). Predicting the production also proves to be quite difficult by conventional methods due to the lack of a baseline (resulting from the change from on-site to off-site operations). Simulation proves to be an adequate tool for this purpose due to its flexibility and capability to address uncertainty within the evaluated process. Moghadam et al. (2012b) describe simulation as a computer-based tool that models real objects and processes in order to effectively evaluate different scenarios and facilitate the decision-making process prior to implementation. Li et al. (2013) develop a multi-scenario simulation in order to evaluate the cost, risk, and production time for a given project on a modular production line. Moghadam (2014) also develops discrete event simulation (DES) models in order to evaluate different solutions to improve the production line of a modular facility and its hoisting equipment. Liu et al. (2015b) propose a specific purpose DES model in order to integrate the BIM model as a feeder to the simulation model for panelized construction. This research proposes the use of simulation as a tool to express the requirements and expectations of the manufacturing department, and direct other stakeholders to provide information for the planners in order to feed the simulation model and predict the productivity incurred from the process using the BIM model as a hub of information for the overall coordination process.

CHAPTER 3 METHODOLOGY

Table 3.1 demonstrates the mapping of the current challenges identified in this research, as well as the research objectives and necessary research steps in order to complete the proposed scope of research. Each of these steps is further described below.

Table 3.1 Mapping of BIM implementation challenges, research objectives, and steps

BIM Implementation challenges	Research Objectives	Research Steps
Lack of communication between different stakeholders	**Objective I:** Evaluate various stakeholder needs in regard to the 3D model, and develop a set of requirements in order to produce the BIM model ***Benefits:*** Improved workflow and integration among the different stakeholders	**Workflow improvement among stakeholders** • Evaluate the current workflow • Identify the needs of each stakeholder • Apply ontology principles to stakeholder's needs with workflow • Develop a set of procedures in order to produce the required BIM model
The quantity takeoff process is tedious and error-prone	**Objective II:** Obtain pertinent information and quantity takeoffs with a high level of automation consistently through different projects ***Benefits:*** Significant time reduction in the takeoff practice while adding more security into the process	**Quantity takeoff process improvement** • Define the necessary level of detail in the BIM model in order to be effectively used by modular practitioners • Connect cost items to BIM model • Adapt units of measurement according to requirements and UOM in cost estimation • Measure level of automation in parametric estimation
Lack of interoperability between BIM models and bidding process	**Objective III:** Adapt the proposed framework for bids and general contracting while maintaining the level of automation applied in the original framework ***Benefits:*** More transparent bid process and change management	**Framework for general contracting** • Define the necessary level of detail in the BIM model in order to be effectively used by estimators during the bidding phase • Evaluate current workflow in analyzed projects • Adapt current procedures for new scenario • Measure current level of automation

Initially, the current workflow will be studied in order to identify any gaps in the process where BIM will be implemented; also, in the case of cost assessment, a parametric estimation will be performed using the BIM model as the central hub of information. Furthermore, the framework will be implemented in another context in order to include general contracting in the bidding process.

3.1 Application of the (i^3) concept: Methodology

As mentioned previously, the development and implementation of this framework utilizes the (i^3) concept as its core philosophy. Figure 3.1 provides a visual overview of the proposed framework, which incorporates the input and criteria pertinent to this research processed by the (i^3) concept, taking into consideration the different perspectives (e.g., architects, plant managers, estimators, etc.) in an integrated approach. As previously described, the (i^3) concept is depicted as the integration of (1) information, (2) intelligence, and (3) innovation. For the scope of this research the (i^3) terms are depicted as follows: (1) information corresponds to the inputs of all stakeholders that comprehend drawings, BIM models, cost items, manufacturing specifications, unit rates, and productivity time studies; (2) intelligence is depicted through the ontology developed in this research in order to guarantee a link between the cost items, elements from parametric models, and the simulation model in order to forecast the labour required for the prefabrication of wood panels; while (3) innovation is delivered through the automation of several steps to provide tailored takeoffs, cost estimation, and assessment of the manufacturing process.

As seen in Figure 3.1, various inputs are considered, including (1) drawings, (2) cost estimation, and (3) information from the manufacturing plant. The drawings in the BIM model include the building elements, dimensions, and specifications in addition to the floor plans, elevation, and

3D views. The estimation presents the cost items with their respective quantity extracted from the BIM model, unit rates, and units of measurement (e.g., concrete is measured by cubic metre); unit rates, and units of measurement allow the information of cost items to be accurately connected to elements in the BIM model. Input from the manufacturing plant is based on the construction method specific to each plant, past experiences of the manufacturing department, and previous time study information regarding the time and resources used in the manufacturing process of prefabricated wood panels. It is important to note that information is provided by different sources that traditionally do not communicate, therefore the data—although correct—tends not to be shared among different parties, causing misinterpretation and rework for the entire production chain. This research intends to reduce this gap by using the BIM model as an information hub for different stakeholders by loading the 3D model up-front with data pertaining to the project.

The criteria described in Figure 3.1 are LOD, estimation classes, and project phases, which are used to define the progression of the model. The stakeholder requirements and the use of ontology must also be addressed in order to provide automated estimations, customized reports, standardized procedures, and the simulation model while producing the BIM model and establishing a transparent workflow between stakeholders and their respective expectations.

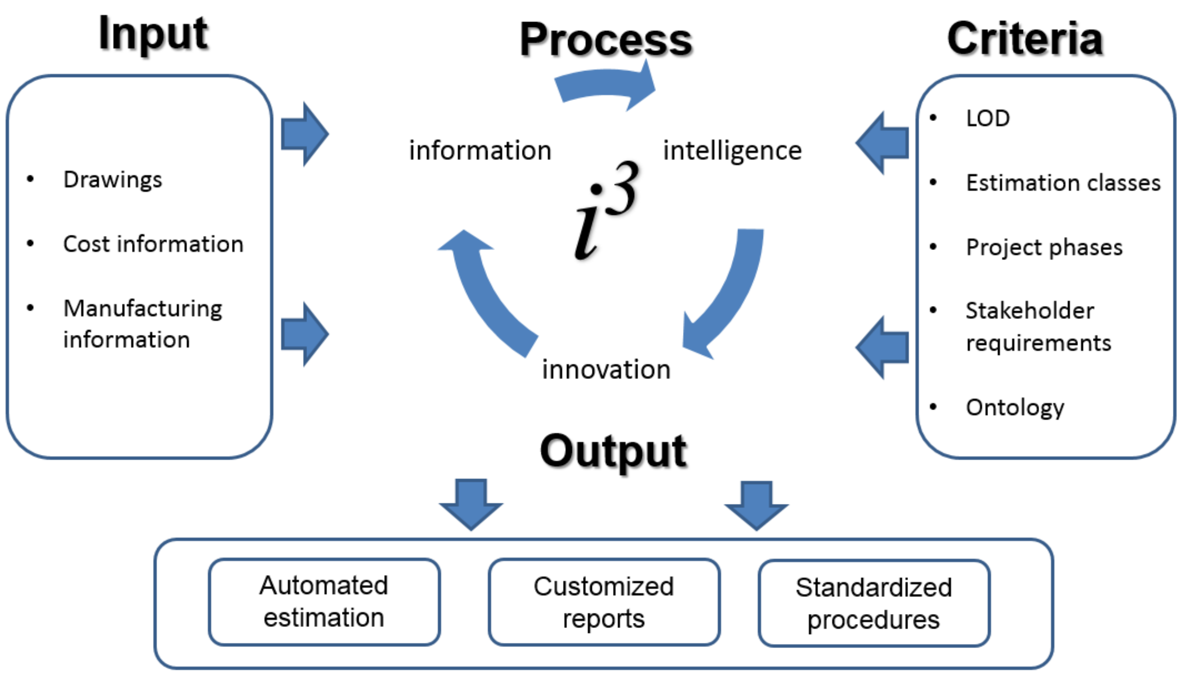


Figure 3.1 Overview of research approach

In order to accomplish the objectives, this research performs a process mapping of each department role in the proposed framework and the information provided. Figure 3.2 presents a flowchart illustrating the material provided and the departments involved. Cost items and unit rates are provided by the estimating department and are extracted from the cost database that may be contained in a simple Excel spreadsheet or represented through Enterprise Resource Planning (ERP) software depending on the size of the company in question. The information needed from the manufacturing plant is included in this database through the cost items and units of measurement. These takeoffs are not common to the current stick-built practice, in which many estimates are simplified (e.g., wall framing is usually estimated per floor area whereas, in a modular facility, the framing must be detailed per each component). The information pertaining to the framing structure is then exported to, and combined in, an Excel spreadsheet, which is used due to its interoperability with Vico Office—the program used for estimation. Add-ons in

Excel are programmed in order to rearrange the combined data to accommodate the formatting requirements and accomplish this step in a timely manner.

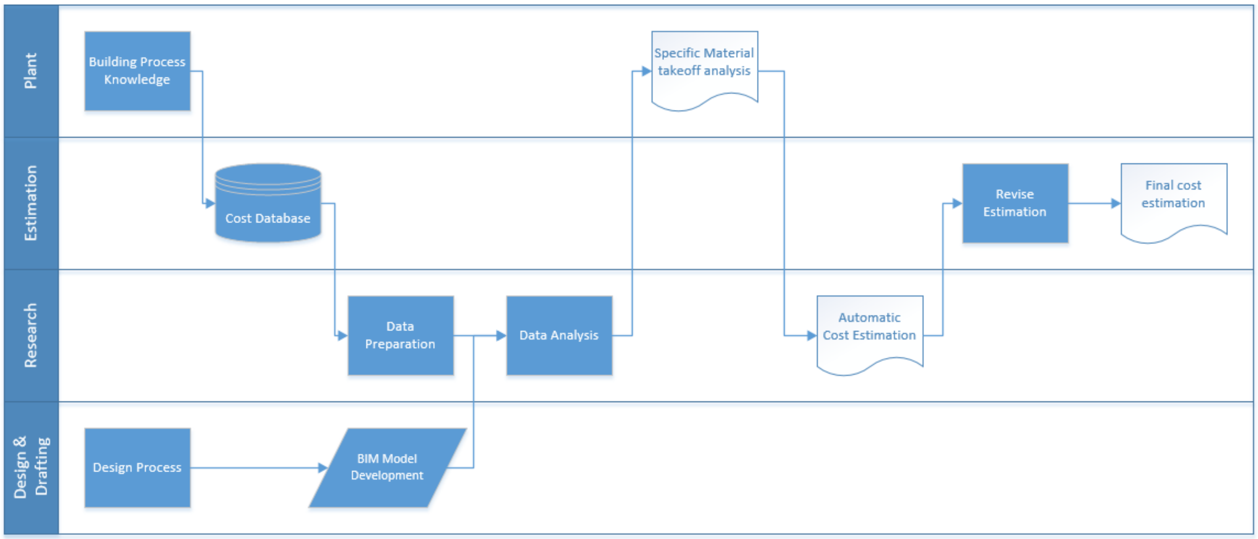


Figure 3.2 Schemata of primary steps

The BIM model is prepared by the design department as per the base model of the project and includes customizable client options such as room sizes, finishing materials, and fixtures. Due to the variety of client options, each project is a unique product hence, a significant effort by the design and cost estimation teams is required to deliver the final product with the correct customizations to the client. The estimation is developed by connecting 3D elements from the BIM model with cost items from the cost database as described in Equations (3.1) and (3.2) below.

$$SOW_i = f(QTO_i^{BIM}) \times \$_i^{Cost} \quad (3.1)$$

$$TOTAL = \sum_1^n SOW_i \quad (3.2)$$

Where:

SOW_i = the total cost of scope of work i in the project

$f(QTO_i^{BIM})$ = the formula of takeoffs required to estimate the scope of work i extracted from the BIM model

$\$_i^{Cost}$ = the set of unit prices required to estimate the scope of work i extracted from the cost database

$TOTAL$ = the total cost of the project

This practice intends to achieve high levels of automation in non value-added and repetitive tasks such as quantity takeoffs. In order to reach this level of integration, the combination of information from various stakeholders is required. This research develops a set of procedures in order to integrate information that has been provided by the stakeholders (estimating, construction, and design departments), and is based on the developed ontology by using the BIM model as a visual database of the construction project in order to automate the cost estimation process. This framework has been initially developed at Landmark Group of Companies, a major Alberta home builder, and has been later extended to encompass requirements from a major modular contractor located in New Brunswick, Kent Homes. The research framework comprises a set of procedures with the objective of integrating diverse information into the BIM model and treating the model as a visual database with the intention of improving several processes in a construction company. Quantity takeoffs is a time-consuming process with the potential for errors and rework when carried out manually. The development of this framework is divided into three key parts: (1) the BIM model development by the drafting department; (2) the integration of information provided by the Project Management Office (PMO), which is adapted for each of the case studies; and (3) the materials and information added to each cost item per category (e.g., wall, floor, etc.).

3.2 BIM model development

This stage consists of the development of design and shop drawings according to purchased product and client modifications. From the base model, the design department must implement all changes and provide all shop drawings required for construction. The developed set of procedures must initially acknowledge, clarify, and communicate to all parties involved that, in contrast to conventional CAD files, elements in a BIM model represent more than merely lines and hatches. Instead, these elements carry important data that transcends traditional drafting and design requirements with the potential to be used by various stakeholders throughout the project life cycle. Drafters must understand the importance of their role in the project life cycle as modelers of valuable pieces of information such as quantity takeoffs and other specifications which will be used throughout the project. This segment of the development process includes the objectives by which to properly fit BIM models in order to accommodate information which is not related to drafting, and to automate quantity takeoff.

3.2.1 Ontology applied for BIM-based naming conventions

In this research, Vico Office is used to perform the quantity takeoff based on BIM models, which is made possible by creating formulas connecting the geometry of specific elements to cost items. These mathematical models become the link between the 3D model(s) and any other information needed to be connected to its element quantity. As with any other database, input data must follow certain naming conventions and formats which, in this case, is carried out by any drafting software such as Autodesk Revit ®. Moreover, the naming of these elements must attend to the requirements from everyone involved in the process to be effective and enhance the process as a whole. An ontology is developed in order to depict all stakeholders and their requirements during the design development stage, resulting in a naming convention applied to every element in the parametric model as a set of procedures in order to guarantee accurate flow of data in the proposed framework. Table 3.2 demonstrates each stakeholder involved in the process and their respective parameters (and abbreviations) required for the proposed framework. As described below, Design & Drafting parameters are deeply related to visual features (e.g., Appearance, Section, and Shape) in the model and its ability to document all existing specifications to be shown in the final drawings such as the ID and Use features. The PMO, with a focus on the estimation process, is more dependent upon the model to depict element specifications regarding its difference in the unit price, while the Manufacturing department features are related to the construction of panels and manners to identify the elements based on location such as the location where the panels are built.

Table 3.2 Stakeholders and their parameters required for proposed framework

Design & Drafting	PMO	Manufacturing
- Appearance (A_p)	- Finishes (F_i)	- Use (U)
- ID (ID)	- Material (M_a)	- Location (L_o)
- Use (U)	- Use (U)	- Size (S_i)
- Size (S_i)	- Size (S_i)	- Connection Type (CT)
- Assembly Number ($A_{\#}$)	- Standard Name (SN)	

Figure 3.3 depicts a visual inter-relationship between the elements contained in the BIM model and stakeholder requirements in the ontology as demonstrated in Table 3.2 and indicated by the different colours assigned per stakeholder. As demonstrated in the figure below, stakeholder requirements are different for each element due to the distinct function and role of the objects in the project (e.g., countertops are identified by the PMO according to M_a parameter while the same element is distinguished by the design & drafting department as per A_p). Furthermore, an example of these naming conventions will be demonstrated on each element together with the criteria selection by the design & drafting department to allow the remaining departments to benefit from this proposed framework

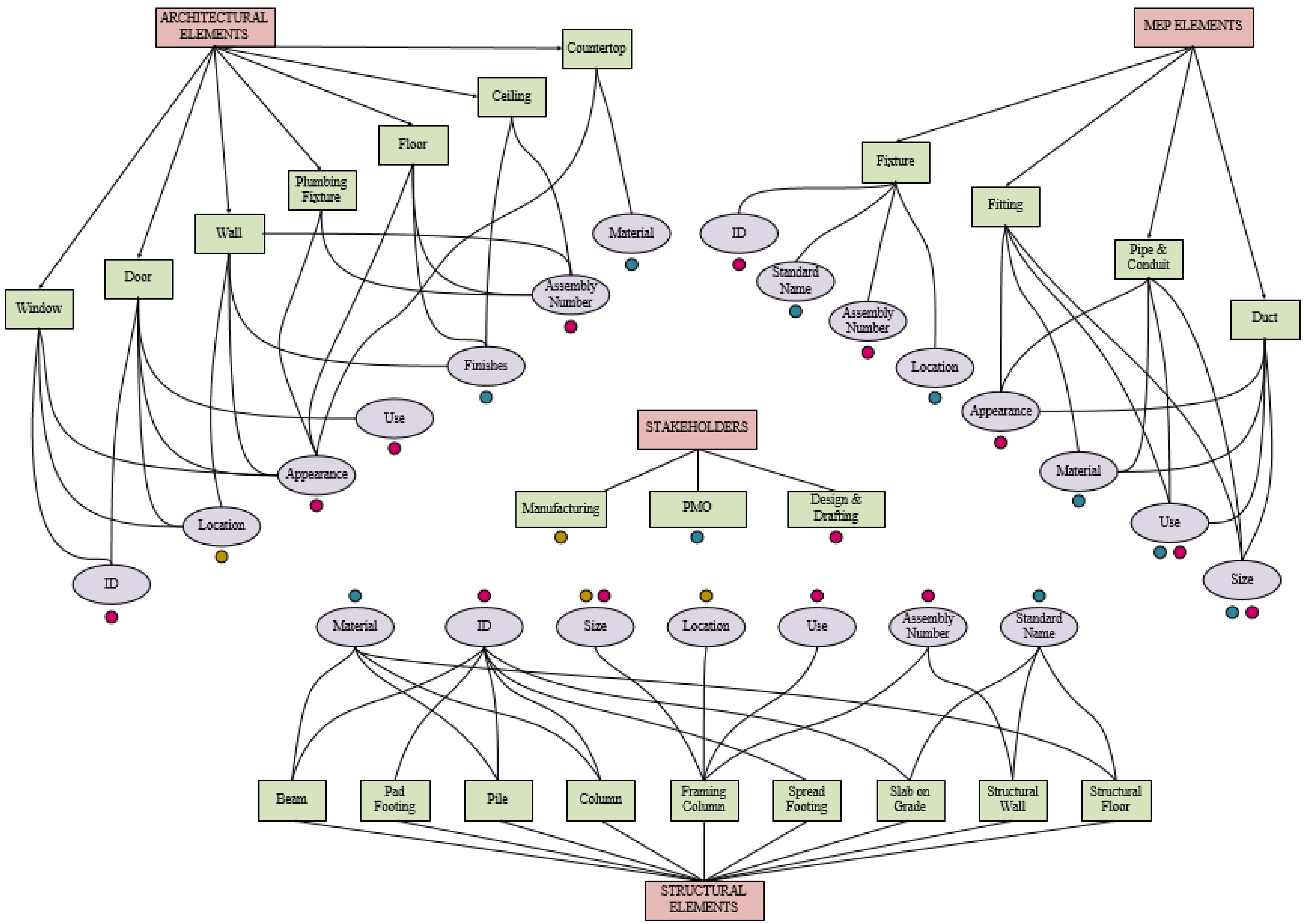


Figure 3.3 Ontology of inter-relationship between BIM-based elements and stakeholders

3.2.2 Naming conventions and criteria selection

Naming conventions as summarized by Tables 3.3, 3.4, and 3.5, which demonstrate the naming convention of each element category of architectural (ARCH), structural (STRC), and Mechanical, Electrical, and Plumbing (MEP), respectively, to fit the proposed framework. Data is entered for all elements through two parameters: *Type name* (T_n) and *Type mark* (T_m). Type name may store the required parameters such as U, ID, S_i, F_i, M_a, and SN with is values being explained through this chapter while T_m (underlined in the examples in order to differentiate the two parameters) is limited to display the L_o parameter required by the manufacturing department when assigning the panel number for fabrication with its values demonstrates by Equation (3.3) below.

$$T_m = \sum_1^{ne} E - ne \, ; \sum_1^{ni} I - ni \;\; ; \sum_1^{nc} C - nc \quad (3.3)$$

Where:

T_m = the location parameter required from the manufacturing department

ne = the number of external panels on the project

ni = the number of internal panels on the project

nc = the number of partition panel on the project

The naming conventions are developed to be generic and are based on assembly numbers in order to allow the user to select different finishes and shapes according to the specific project. In other words, the wall element EXTERIOR 1 ORIGINAL may represent a siding material in one project and stucco in another while maintaining the same formula, and therefore maintaining the accurate quantity in both projects, and the model is not overwhelmed but innumerous types of families. The assembly numbers ($A_{\#}$) are defined prior to modelling and informed to all parties. The selection of material will be demonstrated in the following part of this framework. Another critical step in the modelling procedures is obtaining the correct criteria to select the right type of element at this stage. From the pre-defined pool of elements previously connected to the cost estimation database, the design & drafting department must opt for the correct data entry (element type as described in the BIM model) that is assigned to the correct cost items and information that will later be used as input in the simulation model. The criteria for data entry selection for elements in the BIM model is depicted in Figures (3.4 to 3.9) below.

Table 3.3 depicts the criteria used to name ARCH elements in this framework and illustrates it with an example. As previously mentioned, T_m is underlined to differentiate its parameter from the type name parameter. Wall elements (W_e) are named according to F_i and $A_{\#}$ on each side (e.g., exterior, mechanical, interior, etc.) while the T_m is responsible for assigning L_o as per the manufacturing department request. Floor elements (F_e) are also named under F_i, while windows elements (Wi_e) are simply named after their *ID* designated by the drafting team. Door elements (D_e) are the most difficult of this group due to the number of types (single flush, sliding, pocket, etc.), locations (corridor, exterior, interior, etc.), and features (closer type, lock type, etc.). The initial letter D stands for the element name (Door), and the last letter of its type name stands for its type (e.g., DS1 for single flush, DP1 for pocket, etc.), followed by its ID with the exception DE, which stands for exterior door since several cost items refer to this specific type of door such as finish carpentry hardware, building security, etc. Another special case for naming doors is the use of hollow metal doors, which is represented as HMD—this abbreviation is commonly used by construction practitioners. Countertops and plumbing fixtures are simply named after their material or name, respectively, as demonstrated in Table 3.3.

Table 3.3 Naming of architectural elements

ARCHITECTURAL ELEMENTS		
Data format:	*Type Name + Type Mark*	
Element	**Parameters**	**Example**
Wall	Appearance, Use, Finishes, Location	Exterior-Interior2 E-1
Architectural Floor	Appearance, Use, Finishes	FA 1
Ceiling	Use, Finishes	Popcorn 2
Window	Appearance, Use, ID, Location	W3 E-2
Door	Appearance, ID, Location	DS2 I-3
Countertop	Appearance, Finishes	Granite 2
Plumbing Fixture	Appearance, Use	Toilet

Figures 3.4, 3.5, and 3.6 demonstrate the criteria utilized by the design & drafting department to select wall, floor, and window/door elements, respectively. Figure 3.4 depicts the selection criteria in opting W_e within the proposed framework. As demonstrated, W_e parameters change accordingly with the category (ARCH or STRC) which, in the case of ARCH, the intended F_i and $A_\#$ are identified for each side in order to select the correct element. $A_\#$ is defined on a project-basis and varies according to the construction specifications provided by consultants such as the use of 5/8" type X drywall for Project A and 1/2" type X drywall for Project B on interior walls. On walls with structural use, SN is applied followed by assigning $A_\#$ for the project. A_p is a visual property appearing in the drawings, which is a result of the criteria applied in Figure 3.4 below. L_o defines the panel number utilized by the manufacturing department to identify the panel.

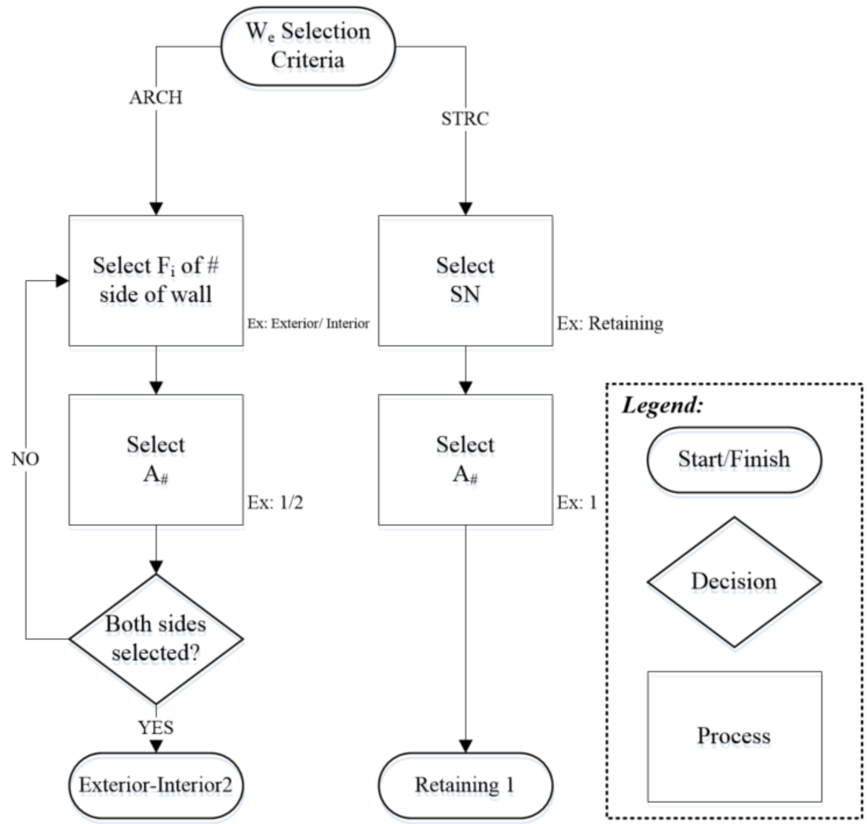


Figure 3.4 Selection criteria for W_e

Where:

$F_i \in \{Exterior, Interior, Partitio, WC, Mechanical, Corridor, Elevator\}$
$SN \in \{Retaining, Parkade\}$
$A_\# \in \{1,2,3, \dots\}$

Figure 3.5 depicts the criteria selection for F_e within the proposed framework. For ARCH, F_i and $A_\#$ are selected based upon the intended design while, in the case of STRC, if the intended floor is a slab on grade, SN is selected followed by $A_\#$. In the case of a structural floor which is not a slab on grade, the initial letter S (for Slab) is selected, followed by the assigned M_a initials (W for wood, C for concrete, and S for Steel) and $A_\#$ parameters as demonstrated in Figure 3.5 below.

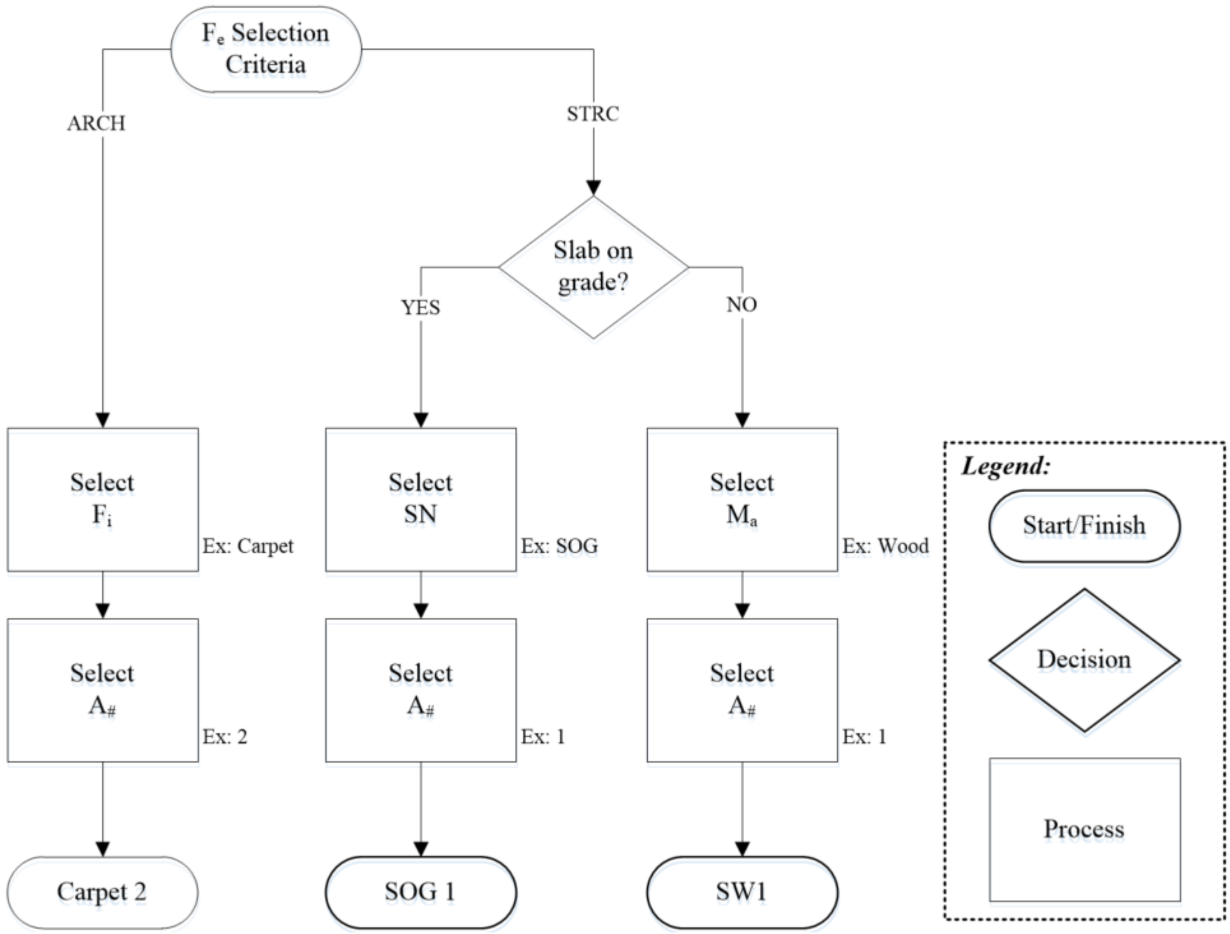


Figure 3.5 Selection criteria for F_e

Where:

$F_i \in \{Carpet, Hardwood, Vinyl, Laminate, Tile\}$
$SN \in \{SOG\}$
$M_a \in \{Wood, Concrete, Steel, Gypcrete\}$
$A_{\#} \in \{1,2,3, \ldots\}$

Figure 3.6 demonstrates the criteria selection used for Wi_e and D_e in the proposed framework. The process is quite similar in both cases, with D_e having the extra parameter U to define the type of door intended for the element, and assigning the correct initial (S for single flush, D for double, O for overhead, L for slide, P for pocket, and E for entrance) as depicted in the drawings by the A_p parameter. In the case of Wi_e, there is no need to define the use since the family use in this framework carries multiple appearances for the same window. The only exception for Figure

3.6 is if a hollow metal door is selected; in this case, D_e will be named by utilizing the SN parameter with the HMD value.

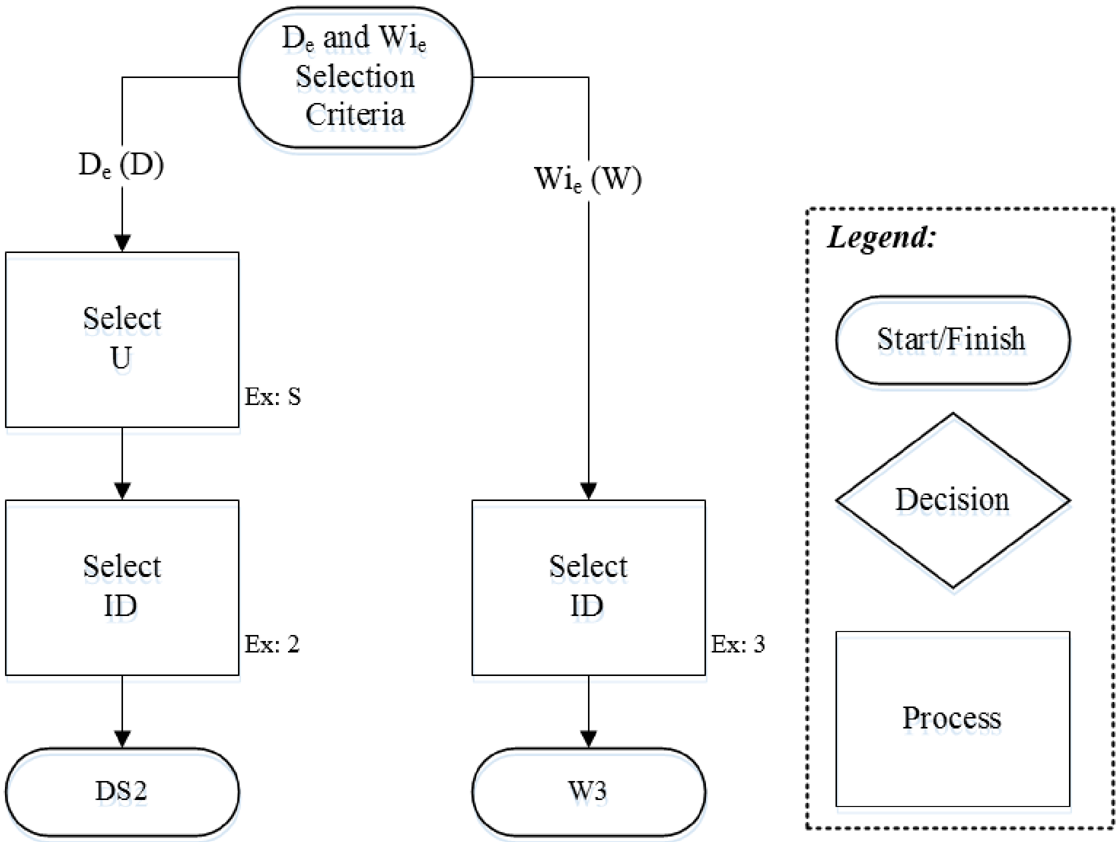


Figure 3.6 Selection criteria for D_e and Wi_e

Where:

$U \in \{S, D, O, L, P, E\}$
$ID \in \{1,2,3, \dots\}$

Table 3.4 demonstrates the naming criteria for structural elements present in this framework (except for framing, which will be discussed later). T_m is not used since the variability of design options is not as wide as architecture and its finishes, and it is heavily limited by the adopted structural system in the project. The naming criteria of the type name parameter is based on known jargons for structural elements used by consultants in order to provide a smoother progression in their culture, and in order to minimize confusion regarding different element names. The first initial for spread and pad footings are named after the structural element (Footing) proceeded by the initial representing its type (Spread and Pad, respectively). Slab on grade constitutes the only element in this group named with three letters (SOG) since it is a common abbreviation widely used by structural engineers. Slab, column, and beams are named in a similar manner where the first initial constitutes the element name and the second letter corresponds to the material used (e.g., Slab Wood 1 as SW1, Column Concrete 1 as CC1, and Beam Steel 1 as BS1, respectively). Figure 3.7 demonstrates the criteria selection for structural elements (S_e), Columns, Beams, and Footings, not demonstrated in Figures 3.4 and 3.5.

Table 3.4 Naming of structural elements

STRUCTURAL ELEMENTS		
Data format:	*Type Name*	
Element	**Parameters**	**Example**
Spread footing	Use, ID	FS1
Pad footing	Use, ID	FP1
Pile	Use, Material, ID	PC1
Slab on grade	Standard name	SOG1
Structural wall	Standard name	Retaining1
Slab (Structural floor)	Material	SW1
Column	Material, ID	CC1
Beam	Material, ID	BW1

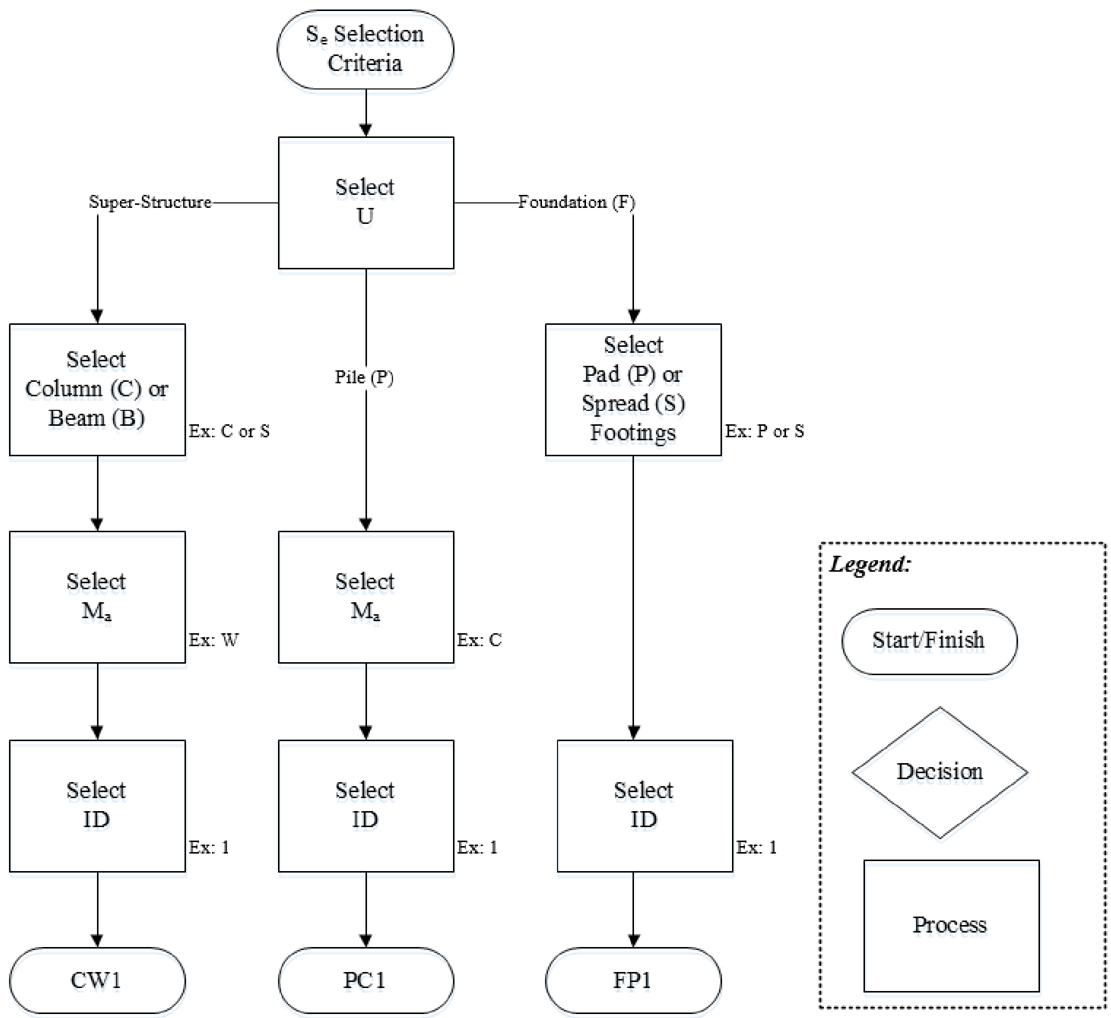


Figure 3.7 Selection criteria for S_e

Where:

$U \in \{S, D, O, L, P, E\}$
$ID \in \{1,2,3, \dots\}$
$M_a \in \{Wood, Concrete, Steel, Screw\}$

MEP elements are demonstrated at Table 3.5 according to the criteria for naming each type name as well as an example to illustrate each case. In this particular section, the size parameter must be added due to different pipe, conduit, and duct sections, and must be accounted for due to the different cost imposed by the diameters of the various elements. Figure 3.8 demonstrates the criteria utilized for naming MEP elements.

Table 3.5 Naming of MEP elements

MECHANICAL, ELECTRICAL & PLUMBING ELEMENTS		
Data format:	*Type Name + Size*	
Element	**Parameters**	**Example**
Pipe & conduit	Appearance, Use, Material, Size	Sewer PVC 100mm
Duct	Appearance, Use, Material, Size	Flex Round Galvanized 25mm
Fitting	Standard name, Material	Elbow 45 PVC
Mechanical fixture	Use, Location	Fan 1
Lighting fixture	Use, Location	Recessed 1
Electrical fixture	Use, Location	Duplex Wheatear

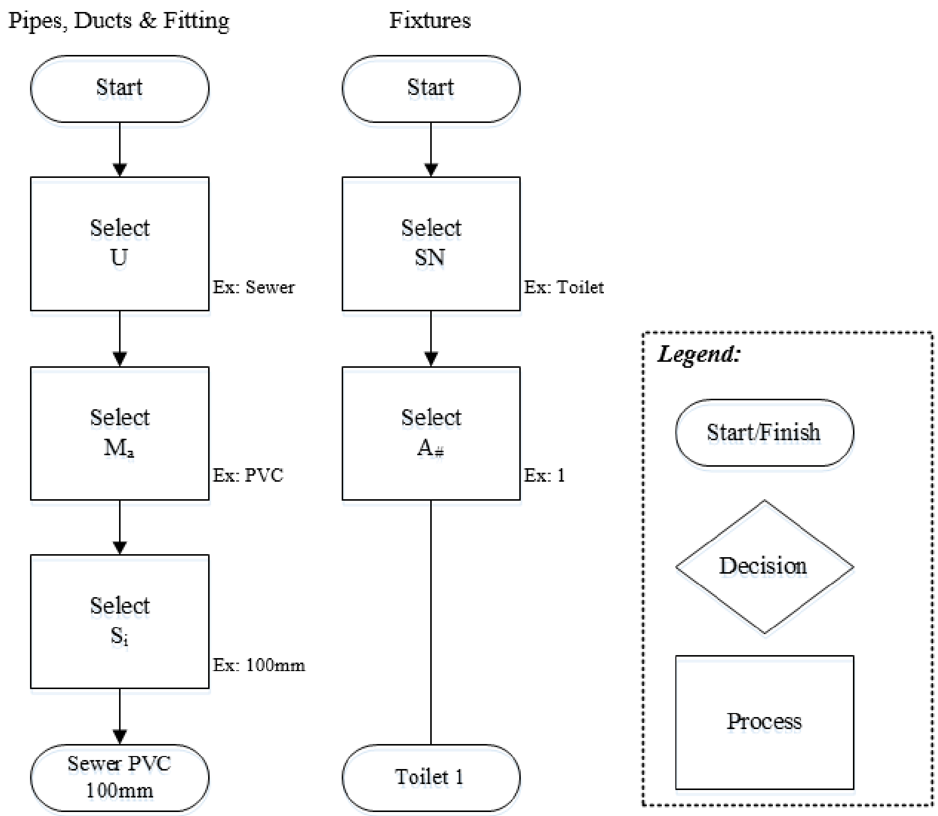


Figure 3.8 Selection criteria for MEP elements

Where:

$U \in \{Sewer, Storm, Hot\ water, Cold\ Water, Supply, Return, 90^o, 45^o\}$
$M_a \in \{PVC, Copper, Steel, Iron\ Cast\}$
$S_i \in \{25mm, 50mm, 75mm, 100mm, 150mm\}$
$SN \in \{Toilet, Sink, Bathtub, Shower, Microwave, Dishwasher, Single\ Pole, Duplex,$

$Threeway, Thermostat, Telephone, Cable\}$
$A_{\#} \in \{1,2,3, \dots\}$

A naming convention for structural framing elements (SF_e) has been develop in order to attend to the specific takeoff requirements from the manufacturing department, which is demonstrated in the first case study presented in this research. More specifically to the wall panels, plant managers must acknowledge the number of elements (studs, plates, nails, etc.) by panel, and the components in each wall such as intersections, windows, doors, etc. Moreover, other assemblies derived from furniture (cabinets, mirrors, etc.) or fixtures, such as the lumber needed to support the boxes from electrical plugs, must be represented in the shop drawings as well as quantified as such for improved planning in the plant and reduction of waste. Those elements must be quantified apart from the conventional lumber present in the panels since their assembly occurs in the next stage of the framing station in order to make the assembly process more efficient (Li, 2016). The type name is composed of the lumber section applied by S_i (e.g., 2x4, 2x6, etc.), two initials described from L_o\ (Exterior, Interior, Partition), and U (Door, Window, Intersection, Corner, Electrical, or Blocking) parameters followed by the designated $A_{\#}$. T_m parameter corresponds to its panel location and number (e.g., E-1 corresponds to Exterior panel 1) as per the manufacturing department and Equation 3.3.

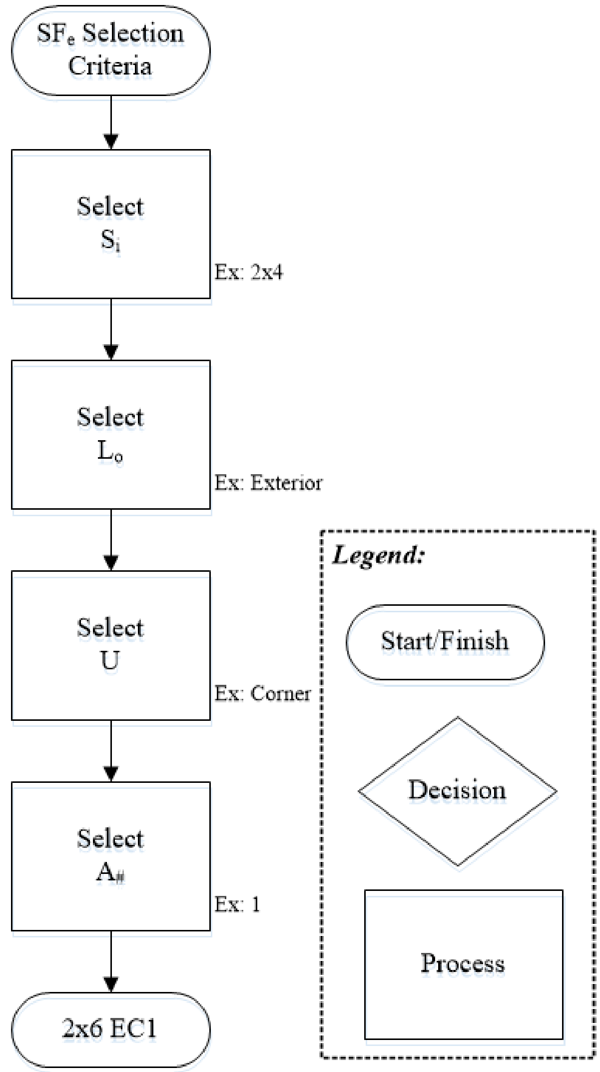


Figure 3.9 Selection criteria for framing components

Where:

$S_i \in \{2x4, 2x6, 2x8, 2x10\}$
$L_o \in \{Exterior, Interior, Partition\}$
$U \in \{Corner, Backing, Intersection, Window, Door\}$
$A_{\#} \in \{1,2,3, \ldots\}$

3.2.3 Modelling procedures

Modelling procedures are also fundamental for BIM modelling in the sense that information must be properly organized and sorted. Since different parties are involved in the design phase, there must be a clear indication of who is modelling each element in order to avoid absence, or duplication, of data (i.e., one column modelled twice) in subsequent stages. Table 3.6 shows the elements that should be modelled corresponding to each work division (in this case, work divisions are defined corresponding to architectural, structural, and mechanical, electrical, and plumbing (MEP) disciplines). Although elements are modelled by various participants in the project, some must be displayed to improve design workflow (e.g., structural walls represented in architectural drawings) and as a requirement for shop drawings. In order to satisfy this need from the design team, a scheme of visibility parameters according to the needs of the design team is developed in this research, as demonstrated in Table 3.6

Table 3.6 Elements modelled according to division of work

ARCHITECTURE	**STRUCTURE**	**MEP**
Stairs	Beams	Conduits and accessories
Doors/Windows	Columns	Connections
Ceilings	Structural floors	Fire protection services
Walls*	Structural walls	Lighting devices
Architectural finishes (walls, floors, etc.)		Ducts and accessories
Shafts		Electrical devices
Roof		Lighting fixtures
Furniture		Sprinklers
Plumbing fixtures		Pipes and accessories

*Excluding structural walls

Following the traditional workflow in construction design, structural and MEP designs are performed by means of the architectural discipline, which in turn has the most significant elements in the model. Elements in other work divisions tend to support architectural elements, such as structural floors being modeled separately from their finishes, rather than modelling one element with multiple layers (e.g., structural sheathing and carpet). This practice may be seen as a mere detail or even a waste of drafting time; however, it prevents confusion or misinterpretation when addressing the liability of different disciplines in the BIM model and relates every cost item to its designed model. Elements such as plumbing fixtures, lighting fixtures, fire protection devices, lighting devices, and appliances constitute a special case: they are manipulated by multiple parties as they are located and connected using pipes and conduits by architectural and MEP drafters, respectively. In order to define which team should model each component, in this research the element ownership is given to the team that places it in the model. Despite their possession, these elements must contain connections and properties that link their geometry to MEP elements (pipes, wires, or ducts) in order to allow other teams to interact with the same parametric object. Figure 3.10 demonstrates the relationships among elements displayed in every discipline in the BIM model, fulfilling the drafter's needs without any extra work on their part. Following the same workflow mentioned above, elements created by architects are presented in other disciplines according to the interaction of these elements with other components (e.g., the interaction of plumbing fixtures from architecture with the pipes and connections at MEP). It is important to note that, despite the quantity takeoff being performed by Vico Office, this methodology is not tailored to any particular drafting software. Therefore, design teams are free to use any BIM software on the market to perform these procedures.

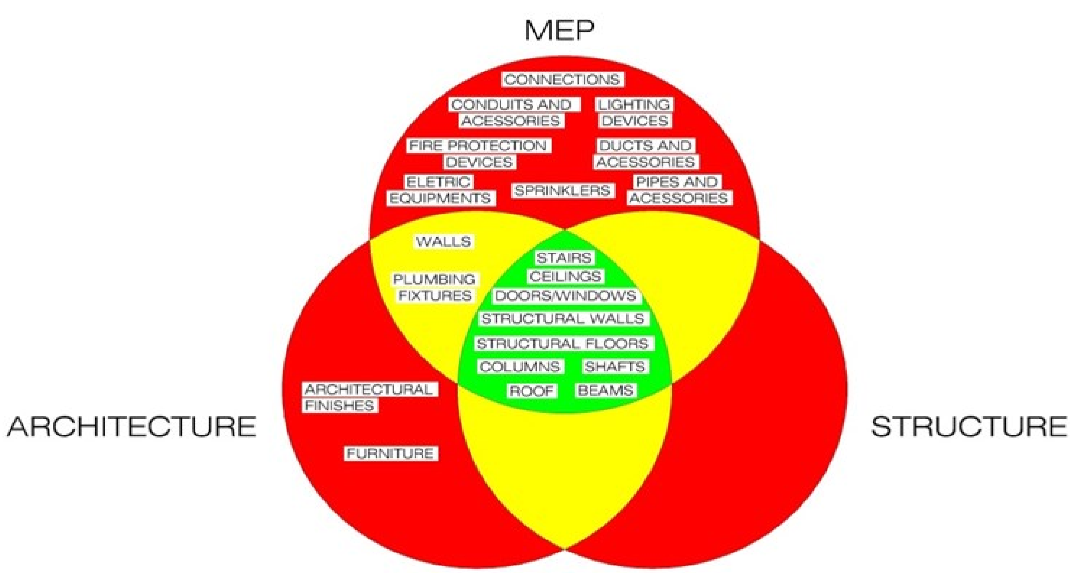


Figure 3.10 Visibility scheme for elements in BIM model according to division of work

3.3 Integrating multi-department data and connecting to BIM model for Construction Manufacturing

This phase is concerned with providing information from the PMO departments to be linked to the BIM model provided by designers. Initially a stakeholder analysis will be conducted for this specific context followed by a description of how the information is distributed and shared among the involved stakeholders.

Three stakeholders are commonly employed during the product development phase: the design & drafting, PMO, and manufacturing departments. They must work closely with one another in order to achieve the success of the project. This is specifically important because, in the case of off-site construction, any mistake could be amplified due to the scale of production, and may also delay the fabrication line with other products in queue. The design & drafting department is responsible for developing the initial drawings for permits and providing the plans (floor plans, elevation, section, etc.), architectural specifications, and the project coordination between the different design disciplines. PMO is responsible for the financial assessment of the project and provides the architectural takeoffs (e.g., flooring area, volume of concrete, etc.) and cost estimation for the project. The manufacturing department deals with the fabrication of the modules that are assembled in the plant, and, at the development phase, produces specific takeoffs for fabrication (e.g., number of nails, drywall sheets, etc.), 3D elements for better visualization, and fabrication specifications such as installation instructions based on constructability studies. Table 3.7 displays the deliverables provided by each department (design & drafting, PMO, and manufacturing) and their use by area of influence.

Table 3.7 Deliverables and impact between departments

		Design & Drafting	PMO	Manufacturing
Deliverables		Plans Architectural specifications Project coordination	Architectural takeoffs Cost estimation	Fabrication takeoffs 3D elements Fabrication specifications
AREA OF INFLUENCE	Plans	X	X	X
	Architectural specifications	X	X	
	Project coordiation	X		X
	Architectural takeoff	X	X	
	Cost estimation		X	
	Fabrication takeoff			X
	3D elements	X		X
	Fabrication specifications	X		X

Table 3.7 illustrates the importance of reliable information shared among the stakeholders since, when it becomes available to one, other departments will also use the data provided for their own work. Design & drafting provides the initial information (plans) for the rest of the departments, and continues to develop the project by adapting the model with information provided by the different stakeholders involved, including architectural specifications and project coordination. The PMO, with possession of the plans and architectural specifications, performs takeoffs and cost estimation while manufacturing works closely with design in order to coordinate the framing process and provide its deliverables. Moreover, all information exchanged is modified and updated a significant number of times due to feedback from other parties involved and project definitions. Therefore, it is essential for the framework to ensure that all data is consistent within the entire coordination process, otherwise the gaps in information may cause a high level of rework, conflicts, and loss of productivity.

Figure 3.11 demonstrates the data flow between stakeholders and information pertaining to the cost estimation process. The process begins with PMO, which provides the cost of every project with its customized modifications and specifications from the sales department and the client. Through the ERP software, cost items with material specifications are entered according to the project specifications as the estimation begins to take shape. These cost items are pulled from a database with diverse information (e.g., units of measurement, key code, unit price) to be used by PMO; its quantities, at this stage, have a default setting of one per item and will be connected to the BIM model in the next stage.

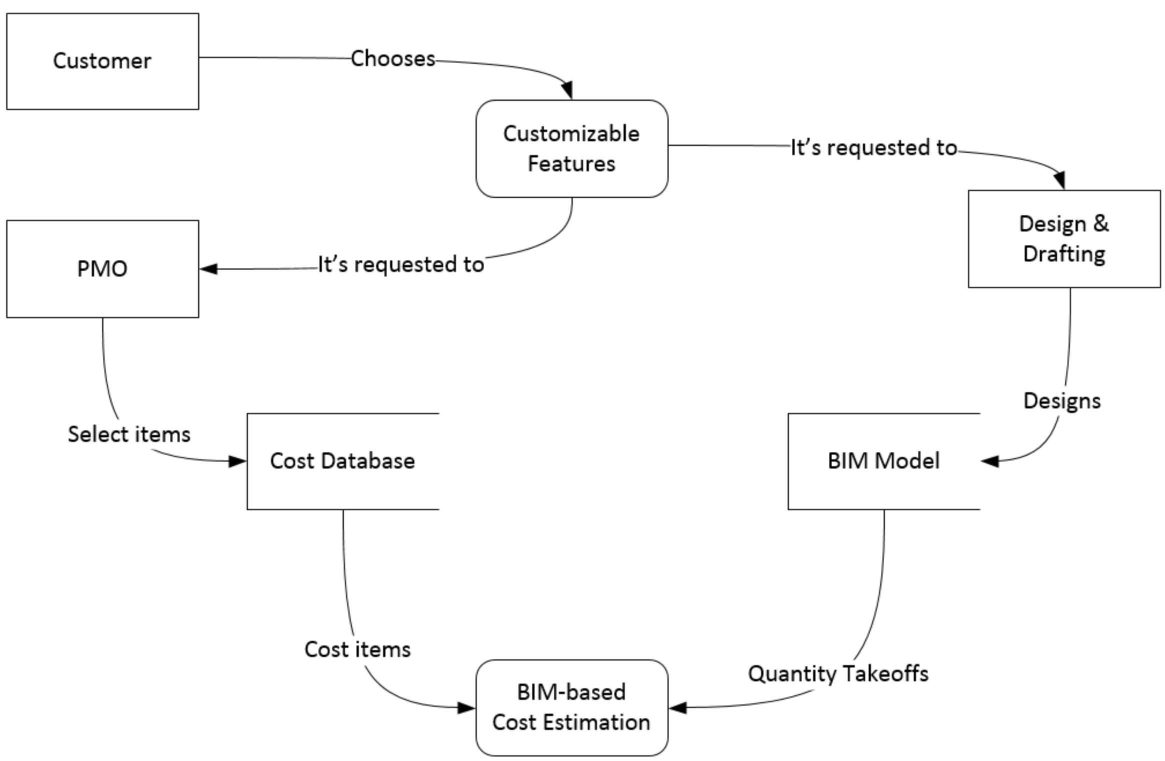


Figure 3.11 Data flow diagram of cost estimation process

Some of these items will maintain the default quantity of one (e.g., lot, building permit, design fee, etc.), while other quantities will change in relation with the construction itself such as concrete, floor finishes, and formwork. The processes of extracting these quantities are time consuming, error prone, and do not add any value to the subsequent phases of a construction project such as estimating and scheduling. The BIM model provided by the design department is used to improve this process and provide more confidence in the information being transmitted from sector to sector. The BIM model alone is not able to provide all takeoffs for construction in an integrated manner with other documents such as an estimation spreadsheet. The author has used Vico Office in order to perform takeoffs and integrate them with other documents provided by other departments such as PMO. Table 3.8 demonstrates the information gathered from the cost database used by PMO to perform the estimation and its integration with the BIM model provided by the design department in Vico Office.

Table 3.8 Information needed to perform estimation and its relationship with design department

Key code	Description	UOM	Consumption & Waste	Unit cost	Formula	Quantity	Total cost

As displayed in Table 3.8, the information provided by PMO contains the following columns, which are already provided by the database: Key code, Description, UOM, Consumption & Waste, Unit cost, and Formula. The remaining two columns, Quantity and Total cost, are filled during the estimation process. Key code depicts the code that makes the item unique in the database, while Description describes the cost item to the user. UOM stands for unit of measurement (e.g., SF, M2, etc.), Consumption & Waste constitutes a percentage to be added on some items that may need a conversion of units or a waste factor due to the construction process, and Unit cost represents the unitary cost of the respective item. The Formula column constitutes the link between the PMO and design departments through the geometry of the elements in the BIM model, which are developed by the naming conventions demonstrated in Tables 3.3, 3.4, and 3.5. These formulas are developed as follows: (1) according to the cost item being estimated, and (2) with the geometry of building elements represented in the BIM model. Great effort has been made in this research to rationalize the quantity of elements to be modelled in order to extract the greatest amount of information with the minimum number of elements in the BIM model through the formulas. For example, rather than modelling door casings, the perimeter and the door width are subtracted so the length of the casings can be quantified. The accuracy of this parameter is crucial for the improvement of the entire process since it guarantees a reliable exchange of information between the design department (represented by the BIM model) and its subsequent departments such as manufacturing and PMO. Equations (5-13) demonstrate how the information is retrieved from both databases and combined in Vico Office in order to estimate the cost of 2x6 wood studs in the overall project (Equations (3.4 to 3.8)) and specific to a particular panel (Equations (3.9 to 3.12)) attending to the requirements from the PMO and manufacturing departments, respectively. T_m variable corresponds to the L_o parameter as discussed in Section 3.2.2.

Formula to estimate 2x6 regular studs

$$2x6Stud = f(QTO^{BIM}_{2x6Stud}) \times 2x6Stud^{Cost} (3.4)$$

$$f(QTO^{BIM}_{2x6Stud}) = \sum_{Mark} 2x6Stud^{BIM}_{Mark} (3.5)$$

$$f(QTO^{BIM}_{2x6Stud}) = [2x6Stud^{BIM}_{Mark-1} \quad \dots \quad 2x6Stud^{BIM}_{Mark-n}] (3.6)$$

$$2x6Stud^{Cost} = \sum_{Mark} 2x6Stud^{Cost}_{Mark} \ (3.7)$$

$$2x6Stud^{Cost} = \begin{bmatrix} 2x6Stud^{Cost}_{Mark-1} \\ \vdots \\ 2x6Stud^{Cost}_{Mark-n} \end{bmatrix} (3.8)$$

For Exterior Panel 1: Mark = E-1

$$f(QTO^{BIM}_{2x6Stud}) = \sum_{i} 2x6Stud^{BIM}_{E-1,i} (3.9)$$

$$2x6Stud^{BIM}_{E-1} = [2x6Stud^{BIM}_{E-1}] (3.10)$$

$$2x6Stud^{Cost} = 2x6Stud^{Cost}_{E-1} \ (3.11)$$

$$2x6Stud^{Cost} = [2x6Stud^{Cost}_{E-1}] \ (3.12)$$

Where:

$2x6Stud$ = the estimated cost for 2x6 studs in the project

$f(QTO^{BIM}_{2x6Stud})$ = the formula to extract the specific takeoff for 2x6 studs

$2x6Stud^{BIM}_{Mark,i}$ = the quantity takeoff of 2x6 studs in the project per panel (mark) and extracted from the BIM model

$2x6Stud^{Cost}$ = the unit price of 2x6 studs in the project extracted from the cost database

$2x6Stud^{Cost}_{Mark}$= the unit price of 2x6 studs in the project per panel (mark) and extracted from the cost database

3.4 Integrating multi-department data and connecting to BIM model for General Contracting

After developing the BIM model according to the stated requirements from different stakeholders and adapting the data, the multi-department information is linked with elements from the 3D prototype. Initially, a stakeholder analysis will be performed in order to better address all the needs of those involved followed by a demonstration of how the connection the information with the 3D elements of the model; model extraction is performed by matching its geometry with the unit provided by PMO for each item for the second case study of general contracting (e.g., concrete is priced in cubic meters, hence the volume of all structural elements are summed into this item). This stage relates cost items from PMO and manufacturing departments with the families presented in the BIM model provided by the design department and is divided by family categories (walls, floors, and doors/windows).

Cost estimation is traditionally performed by the project manager, and relies on personal experience and historical data from previous projects; bids are traditionally based on a lump sum. This method of cost estimation, classified as Class 3 according to the Association for the Advancement of Cost Engineering (AACE), although quite simple, leads to a high level of variation between the estimated cost and bid prices since the information gathered is highly susceptible to the availability of trades at the moment of tender, agreements made at the time, and differences between project characteristics. A suitable solution is the adoption of a Class 2 estimation (according to AACE classifications) based on unitary values despite being time consuming and prone to error due to constant design changes and human mistakes. Hence, BIM appears to be a suitable solution to improve the estimation process while providing a more reliable flow of information to the management team.

Through the second case study, it is discovered that, despite past experience with this technology, the in-house architect and his team do not use BIM tools; although, they regularly rely on conventional CAD applications for their projects and also show interest in the project by providing their feedback and requirements for the framework. The rest of the designs are out-sourced to consulting firms which, despite being able to provide BIM models for an extra fee, provide CAD drawings due to the contracting agreement with the general contractor. The management team indicates a willingness to pay the extra fee to acquire the BIM models from consultants and lists reasons for not investing in BIM as follows: (1) the architectural model is already in CAD, and (2) there is not a clear indication of the extra outcome provided by the parametric models. Therefore, the model must describe the features in all designs while attending to the needs of the design and engineering teams. Since this project is built in the traditional stick-built practice, the manufacturing department is not involved. The requirements from both departments are listed in Tables 3.9 and 3.10 below.

Table 3.9 Requirements from the Engineering department for the developed framework

Engineering department
(a) Automation for a quantity takeoff Class 2 according to AACE
(b) Cost per scope of work and designated areas (e.g., portion of slab or suite)
(c) Reports for sale and financial departments
(d) Compliance with codes used by the company and Masterformat

The framework must provide the requirements listed in Tables 3.9 and 3.10 from both departments by establishing a connection with the BIM model. As mentioned before, a Class 2 estimation must be performed in an automated manner while making the entire estimation process more reliable to the Engineering department. The structure of this document must follow the predetermined organization of the scopes of work, but must also provide the cost as per the designated area. Designated area, or zone, refers to portions of work within the scope usually determined when the work is being planned, and may be portions of the project's slab to be performed concurrently, or may be a more straight forward division such as individual suites at the finishing stage. This feature assists planners in discussions with trades and other processes, such as invoicing and cash flow planning, during the execution of the project. Moreover, the Engineering department must provide information for other departments, such as sales and financials from the estimation document, in order for these departments to define the sales price of each unit and send the estimation to financial institutions, such as banks, in a predetermined format (in this case, Masterformat). In order to accommodate these needs, the framework must generate specific reports for these departments since their structure follows a different logic than that which is used to create the initial document. Finally, since the company is implementing a change in their information management system, two sets of codes are being used, hence the framework must accommodate both codes and generate the reports according to the suitable set of codes (e.g., estimation by scopes of work uses the old set of codes, while the items in the financial report must be organized as per the Masterformat).

Table 3.10 Requirements from the design & drafting department for the developed framework

Design & Drafting department
(a) Drafting automation
(b) Consistency in material specification
(c) Smooth transition between CAD and BIM platforms
(d) Efficient and standardized modelling procedures
(e) Improvement of project coordination with other consultants and subtrades

Items (a) and (b) demonstrated in Table 3.10 are easily achievable since they are common features of the parametric objects modelled in any on-the-shelf BIM application such as Autodesk Revit and Graphisoft Archicad. The biggest challenge on these requirements resides with item (c), which calls for a change in the culture and workflow of the team. Convincing experienced professionals to learn new concepts and implement new tools is not an easy task, especially during the transition period, which involves a time-consuming learning process despite the need to attend to deadlines and deliverables to the clients (in this case, the company). A cornerstone of this transition is a set of procedures and guidelines, represented by item (d), which clarify common practices as well as which objects should be modelled in order to guarantee the availability of all necessary information for the stakeholders involved and spending the least amount of effort from the design team. In summary, the objective of these guidelines is to ensure that more information is being acquired with the least amount of effort from the company employees. Moreover, the design team also requested the improvement of the design coordination with other consultants using the BIM model due to the large amount of information found in the drawings from all consultants and subtrades, which is represented as item (e) in Table 3.10. It can be observed in Tables 3.11, 3.12, 3.13, and 3.14 that some scopes of work appear in multiple occasions such as the “Formwork and rebar” scope since its takeoffs are derived from different types of element (walls, floors, and structural elements) and are estimated using similar formulas as presented in this section.

3.4.1 Walls

This section discusses any information covered by wall elements in the cost estimation. Table 3.11 depicts the 13 different types of walls used in the case studies that are connected to the cost items according to the nature of the item (e.g., fire retardant is applied on exterior walls). As shown in the table, framing & components, drywall & components, and paint are the cost items that correlate with the highest number of wall types since these items are found in most areas of the house.

Table 3.11 Types of wall and corresponding scopes of work

Scopes of Work \ BIM elements	Corridor-Interior	Corridor-Mechanical	Elevator	Entrance	Exterior 1-5	Exterior-Interior 1-2	Exterior-Mechanical	Exterior-Stair	Interior 1-2	Lobby	Mechanical-Interior	Partition-Interior	Partition-Mechanical	Retaining 1-2	Stair-Interior	Storage
Alluminum Entrance				**X**												
Cladding					**X**											
Concrete supply														**X**		
Drywall & components	**X**	**X**	**X**			**X**	**X**	**X**	**X**		**X**	**X**	**X**		**X**	
Finish carpentry- Install	**X**	**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	
Finish carpentry- Supply	**X**	**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**		**X**	
Fire retardant						**X**										
Framing & components	**X**	**X**	**X**			**X**	**X**	**X**	**X**		**X**	**X**	**X**		**X**	
Formwork & rebar														**X**		
Paint	**X**	**X**				**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	
Storage locker rooms																**X**
Weeping tile														**X**		

Equations (3.12-3.16) demonstrate the estimation formula (walls only) for the Paint contract in the proposed framework as an example of how the cost is estimated. As per typical project specifications, there are five types of paint to be estimated separately with its district unit prices: (1) Corridor, (2) Interior, (3) Stairs, (4) Lobby, and (5) Retaining. These specifications are distinct on each side of a wall, as demonstrated in Table 3.11, and correspond to the *finishes* parameter as discussed in Figure 3.4. Once the area of each wall is retrieved from the BIM model (Equation (3.13)), its takeoff is multiplied with its respective estimated unit rate to be later used as a benchmark for the bidding process.

$$Paint = f(QTO_{Paint}^{BIM}) \times Paint^{Cost} \quad (3.12)$$

$$f(QTO_{Paint}^{BIM}) = [\textstyle\sum_1^n Corridor_i^{BIM} + \sum_1^n Interior_i^{BIM} + \sum_1^n Stair_i^{BIM} + \sum_1^n Lobby_i^{BIM} + \sum_1^n Retaining_i^{BIM}] \quad (3.13)$$

$$f(QTO_{Paint}^{BIM}) = \begin{bmatrix} Corridor_1^{BIM} Interior_1^{BIM} Stair_1^{BIM} Lobby_1^{BIM} Retaining_1^{BIM} \\ \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\ Corridor_n^{BIM} Interior_n^{BIM} Stair_n^{BIM} Lobby_n^{BIM} Retaining_n^{BIM} \end{bmatrix} \quad (3.14)$$

$$Paint^{Cost} = [Corridor^{Cost} + Interior^{Cost} + Stair^{Cost} + Lobby^{Cost} + Retaining^{Cost}] \quad (3.15)$$

$$Paint^{Cost} = \begin{bmatrix} Corridor^{Cost} \\ Interior^{Cost} \\ Stair^{Cost} \\ Lobby^{Cost} \\ Retaining^{Cost} \end{bmatrix} \quad (3.16)$$

Where:

$Paint$ = the estimated cost for the Paint contract

$f(QTO_{Paint}^{BIM})$ = the formula to extract the takeoff specific for the Paint contract

$Corridor_i^{BIM}$ = the takeoff for corridor finishes extracted from wall elements; $Corridor_i^{BIM} \in \{Corridor - Interior, Corridor - Mechanical\}$

$Interior_i^{BIM}$ = the takeoff for interior finishes extracted from wall elements; $Interior_i^{BIM} \in \{Exterior - Interior, Exterior - Interior2, Interior1Interior2, Mechanical - Interior, Partition - Interior, Stair - Interior\}$

$Stair_i^{BIM}$ = the takeoff for corridor finishes extracted from wall element; $Stair_i^{BIM} \in \{Stair - Interior\}$

$Lobby_i^{BIM}$ = the takeoff for lobby finishes extracted from wall elements; $Lobby_i^{BIM} \in \{Lobby\}$

$Retaining_i^{BIM}$ = the takeoff for retaining finishes extracted from wall elements; $Retaining_i^{BIM} \in \{Retaining1, Retaining2\}$

$Paint^{Cost}$ = the set of unit rates for the Paint contract extracted from the cost database

$Corridor^{Cost}, Interior^{Cost}, Stair^{Cost}, Lobby^{Cost}$, $Retaining^{Cost}$ are the respective unit rates for the finishes extracted from the cost database

3.4.2 Floors and ceilings

Table 3.12 demonstrates the information covered by the elements in the BIM model for floors and ceilings. It can be observed that, despite the previous case shown in Table 3.11, cost items and 3D elements are related in a one-to-one relationship since, in most cases, the elements are more differentiated by finishing specifications (carpet, hardwood, etc.). Equations (3.17-3.21) demonstrate how the Flooring-Hardwood (Hardwood) contract is estimated within the proposed framework.

Table 3.12 Types of floors/ceilings and corresponding scopes of work

BIM elements / Scopes of Work	Balcony 1-2	Carpet 1-3	Hardwood 1-3	SG 1	SOG 1-2	SW 1-3	Tile 1-3
Balcony coatings	X						
Electrical					X	X	
Concrete supply					X		
Drywall & components						X	
Finish carpentry- Install		X	X				
Finish carpentry- Supply		X	X				
Fire retardant						X	
Floor Joist Supply						X	
Flooring- Carpet		X					
Flooring-Hardwood			X				
Flooring- Tile							X
Framing & components					X	X	
Formwork & rebar					X		
Gypcrete				X			
Mechanical						X	
Sprinkler					X	X	

$$Hardwood = f(QTO_{Hardwood}^{BIM}) \times Hardwood^{Cost} \quad (3.17)$$

$$f(QTO_{Hardwood}^{BIM}) = \sum_{1}^{n} Hardwood_i^{BIM} \quad (3.18)$$

$$f(QTO_{Hardwood}^{BIM}) = [Hardwood_1^{BIM} \quad \dots \quad Hardwood_n^{BIM}] \quad (3.19)$$

$$Hardwood^{Cost} = \sum_{1}^{n} Hardwood_i^{Cost} \quad (3.20)$$

$$Hardwood^{Cost} = \begin{bmatrix} Hardwood_1^{Cost} \\ Hardwood_2^{Cost} \\ Hardwood_3^{Cost} \end{bmatrix} \quad (3.21)$$

Where:

$Hardwood$ = the estimated cost for the Hardwood contract

$f(QTO_{Hardwood}^{BIM})$ = the formula to extract the takeoff specific for the Hardwood contract

$Hardwood_i^{BIM}$ = the takeoff for hardwood finishes extracted from floor elements; $Hardwood_i^{BIM} \in \{Hardwood1, Hardwoood2, Hardwood3\}$

$Hardwood^{Cost}$ = the set of unit rates for the Hardwood contract extracted from the cost database

$Hardwood_i^{Cost}$ = the unit rate for each type of hardwood floor extracted from the cost database

3.4.3 Doors and windows

Doors and windows are demonstrated in Table 3.13, which has a similar relationship as that which is demonstrated in the walls category (Table 3.11) where one cost item gathers information from various elements. Windows information is extracted from a significant number of items due to its high level of use requirements for the project. The formulas to extract pricing from this section are similar to the previous two sections thus will not be demonstrated.

Table 3.13 Types of doors/windows and corresponding scopes of work

Scopes of Work \ BIM elements	DB 1-5	DE 1	DL 1-2	DO 1	DP 1-2	DS 1-6	HMD 1-3	W 1-6
Aluminum Entrance	X							
Building Security System		X				X		X
Framing & components								X
Finish carpentry- Install	X		X		X	X		
Finish carpentry- Supply	X		X		X	X		
HMD/PSF							X	
Overhead Door				X				
Signage- Exterior		X						
Signage- Interior		X						
Window coverings								X
Windows & patio doors						X		X

3.4.4 Architectural and structural elements

Architectural and structural elements are combined and connected to their respective scopes of work as demonstrated in Table 3.14. These elements are modelled according to the design and estimation requirements, and their data must be combined into the framework in advance. On the other hand, other elements must be modelled separately in order to be estimated. The Wire Shelving & Mirrors contract (calculated as per Equations (3.22-3.31)) is a good example of both situations since, in order to quantify shelving, the linear footage must be extracted from the model and connected with its unit cost, while mirrors are quantified by their unit and are not present in the architectural drawings. Contradictory to common practice, shelves are modelled as beams (and not objects) in this framework to extract the length quantity, and the quantities of mirrors are derived from the number of toilets in the model since both quantities are identical (each bathroom has one toilet and one mirror). This practice avoids extra work from drafters and automates one activity for the estimators.

Table 3.14 Architectural and structural elements and their corresponding scopes of work

Scopes of Work \ BIM elements	Bathtub	BC 1-8	BW 1-10	CC 1-5	CW 1-5	Cooktop	Dishwasher	FP 1-5	FS 1-5	JW 1-5	Lavatory	PC 1-5	PS 1-5	Refrigerator	Toilet	TW 1-5	SH 1-3	Sink	SW 1-3	Washer/Dryer
Appliances- Install						**X**	**X**							**X**						**X**
Appliances- Supply						**X**	**X**							**X**						**X**
Bathroom accessories															**X**					
Concrete supply		**X**		**X**								**X**								
Floor joist supply										**X**										
Formwork & rebar		**X**		**X**								**X**								
Framing labour										**X**										
Piles												**X**	**X**							
Lumber supply					**X**														**X**	
Roof truss supply																**X**				

$$WSM = f(QTO_{Shelve}^{BIM}) \times Shelve^{Cost} + f(QTO_{Mirror}^{BIM}) \times Mirror^{Cost} \quad (3.22)$$

$$f(QTO_{Shelve}^{BIM}) = \sum_1^n Shelve_i^{BIM} \quad (3.23)$$

$$f(QTO_{Shelve}^{BIM}) = [Shelve_1^{BIM} \quad \dots \quad Shelve_n^{BIM}] \quad (3.24)$$

$$Shelve^{Cost} = \sum_1^n Shelve_i^{Cost} \quad (3.25)$$

$$Shelve^{Cost} = \begin{bmatrix} Shelve_1^{Cost} \\ \vdots \\ Shelve_n^{Cost} \end{bmatrix} \quad (3.26)$$

$$f(QTO_{Mirror}^{BIM}) \equiv f(QTO_{Toilet}^{BIM}) \quad (3.27)$$

$$f(QTO_{Toilet}^{BIM}) = \sum_1^n Toilet_i^{BIM} \quad (3.28)$$

$$f(QTO_{Toilet}^{BIM}) = [Toilet_1^{BIM} \quad \dots \quad Toilet_n^{BIM}] \quad (3.29)$$

$$Mirror^{Cost} = \sum_1^1 Mirror_i^{Cost} \quad (3.30)$$

$$Mirror^{Cost} = [Mirror_1^{Cost}] \quad (3.31)$$

Where:

WSM = the estimated cost for the Wire Shelving & Mirror contract

$f(QTO_{Shelve}^{BIM})$ = the formula to extract the specific takeoff for shelves in the Wire Shelving & Mirror contract

$Shelve_i^{BIM}$ = the takeoff for shelves extracted from beam elements in length; $Shelve_i^{BIM} \in$ {SW1,SW2,SW3}

$Shelve^{Cost}$ = the set of unit rates for shelves used in the Wire Shelving and Mirrors contract extracted from the cost database

$Shelve_i^{Cost}$ = the unit rate per length for each respective type of shelf extracted from the cost database

$f(QTO_{Mirror}^{BIM})$ = the formula to extract the specific takeoff for mirrors in the Wire Shelving & Mirror contract

$f(QTO_{Toilet}^{BIM})$ = the formula to extract the specific takeoff for toilets used in Wire Shelving & Mirror contract

$Toilet_i^{BIM}$ = the takeoff for toilets extracted from plumbing fixtures in units; $Toilet_i^{BIM} \in \{Toilet\}$

$Mirror^{Cost}$ = the set of unit rates for mirrors used in the Wire Shelving and Mirrors contract extracted from the cost database

$Mirror_i^{Cost}$ = the unit rate for mirror extracted from the cost database

CHAPTER 4 APPLICATION OF THE (i^3) CONCEPT: CASE STUDIES

This section presents two case studies, which encompass the scope of research. The first example applies the framework to the requirements of planners in modular construction facilities, which include detailed material takeoff, and automatic quantification of wood-framing modules. These are existing requirements from the manufacturing department of a case prefabrication facility in Fredericton, New Brunswick. The second case study comprehends the automation of takeoff and estimation of most items along with the required coordination between disciplines by applying the proposed framework to a 4-storey building project located in Edmonton, Alberta. Both case studies follow the same structure of components: (1) introduction and background of the project in question; (2) discussion regarding the appropriate level of detail for the BIM model; (3) presentation of the cost breakdown structure; and (4) model features and results from the proposed framework.

4.1 First case study

The first application of the (i^3) concept consists of a 2-bedroom single-family residential project divided into two modules produced in a modular facility of Kent Homes, as demonstrated in Figures 4.1 and 4.2. Kent Homes is committed to process enhancement by eliminating waste in daily activities, upstreaming wall panel production in 2D motion, and investing in the pre-assembly of components in order to accelerate the production line. As previously mentioned, the company provides a wide range of customization to its clients (finishes, room resizing, etc.), meaning many different types of modules (products) are being put through the production line due to the high variability imposed by the client. This, and the high volume of projects, directs the parties involved in product development to act concisely toward each different product in order to be efficient and avoid rework. This research aims to identify the current stakeholder needs during the product development phase, map the development of the BIM model through the process, and suggest a workflow to improve the exchange of information for off-site construction projects. First, the stakeholders in the process are identified by their current needs and deliverables to the project. Second, a discussion is presented about the progression of the BIM model detailing and the effort required to achieve it. Third, an approach in order to satisfy the needs of off-site construction practitioners and the work performed by the BIM model is presented.

Figure 4.1 Floor plan of first case study

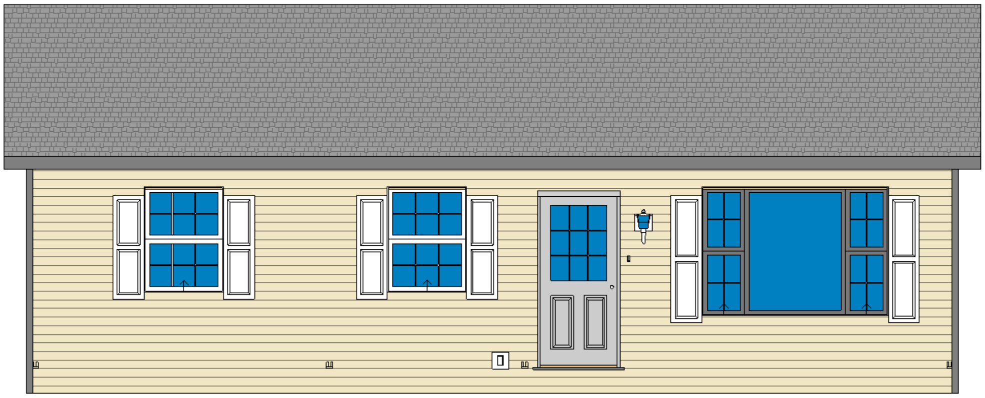
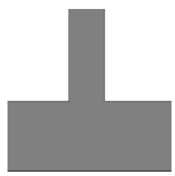
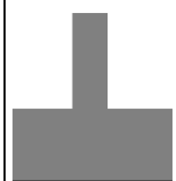
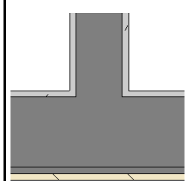
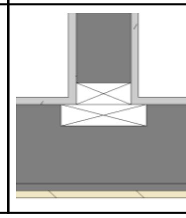
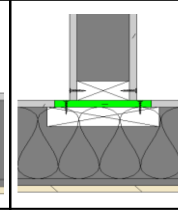


Figure 4.2 Elevation view of first case study

4.1.1 Discussion about the BIM model progression

In order to conduct the discussion, an example is provided to illustrate the drafting effort and the information able to be extracted from models with different LODs, as well as the information added through the process. Table 4.1 demonstrates the progression of the BIM model according to its design stage, achievable estimation class, information added, as well as an illustration and the number of elements modelled to achieve the required LOD. A connection between exterior and interior walls is chosen since it is common to every project and portrays the necessary interaction between the design and manufacturing departments. It can be observed that the definitions of LOD and the design stages are not synchronized through the BIM model progression; hence, some LODs are achieved between the two stages. More information from departments other than design & drafting is added from LOD 300, which occurs at the end of the design development stage, and when the architectural design reaches a significant maturity. At this level, it is possible to produce an estimation for budget authorization, which means that it is possible to define with a significant confidence what the total cost of the project will be. More accurate estimations are performed in the following stages as the project becomes more defined and information is added/extracted from the BIM model. The estimation's class follows the progression of the BIM model since its definitions are related to the definition of the project.

Table 4.1 Progression of BIM model through its coordination stages

LOD	100	200	300	350	400
Design phase	Schematic	Design development	Design development	Construction documents/ Bid	Bid/ Construction
Estimation class	Class 5	Class 4	Class 3	Class 2/ Class 1	Class 1
Information available at mentioned LOD	-Project screening -Feasilbilty	-Takeoffs for permits and detailed feasibility studies -Plans	-Architectural specifications -Plans -Cost estimation (Budget authorization)	-Design from consultants -3D elements -Fabrication specifications	No information related to the scope of this research
# of objects modelled	2	2	2	4	25
Screenshot					

From Table 4.1, it can be observed at LOD 300 that the architectural specifications begin to be fed into the model, hence material information is displayed (in this case, interior and exterior substrate). Cost estimations for budget authorization are possible to be performed with this level of detailing since the specifications are available and most of this information does not need to be portrayed at the delivered drawings. When the model achieves LOD 350, a simplified version of the consultants' designs is available (e.g., plates, studs, backframing, etc. for wood framing), which allows the project coordination in regard to clash detections, and the adaptation of all disciplines into the project. An additional number of elements are modelled, but their geometries must be represented so an interference check analysis between different disciplines can be performed in order to identify/adapt the current design; for example, adding new openings in the framing designs due to HVAC penetrations in walls and floor panels.

All fabrication specifications, although defined, are not graphically represented in the model, such as the drywall used between the walls in order to fire rate the entire structure, nor the drywall screws or type of insulation used. These types of information are only represented graphically when an LOD 400 is achieved and all specifications (architectural and structural) are demonstrated. The number of modelled elements to achieve an LOD of 400 increases more than six times due to minor elements such as the nails used to connect studs to the plates, and the fire rated drywall between walls. Moreover, these elements must be modelled manually, increasing significantly the modelling effort and, despite its visual appeal, adds little information to the entire process since these takeoffs can depend on previously modelled elements in earlier stages (e.g., the takeoff of nails can be dependent on the number of studs and plates modelled in LOD 350). Hence, having a more detailed model (in terms of geometry) does not necessarily add more value to the overall process since extra modelling effort must be performed to provide information that could be extracted indirectly from existent elements in the prototype. A better clarification of this process is presented in the following section.

4.1.2 Cost breakdown structure

The shift in the development phase of an off-site construction project is mainly driven by the manufacturing department, and requires information not commonly required by the stick-built practice. As an example, a quantity takeoff is required for the number of window components on each panel, rather than the total project, for production planning and material storage. This, and other necessary information, is added in the cost breakdown structure used by PMO, and is aligned with design & drafting in order for this data to be entered at the earlier stages of the BIM model. Table 4.2 indicates the breakdown structure used in this case study, while a complete breakdown can be found at Appendix A of this thesis. A high level of detail is present due to the information required by the manufacturing department such as corner components, as demonstrated below.

Table 4.2 Breakdown structure for first case study

Level	Key Code	Description
1	W	Wall Panels
2	WE	Exterior Walls
3	WE-01	Exterior Wall Panel 01
4	WE-01-WFRA	Framing
5	WE-01-WFRA-#01	2x6 Stud
5	WE-01-WFRA-#11	Component
6	WE-01-WFRA-#11-#001	Corner

Figure 4.3 distinguishes framing components by type and use as demonstrated in the selection criteria for framing components depicted in Figure 3.9. It can be noted in Figure 4.3 that the corner component (marked in red) is named differently due to its use in comparison to the remaining regular studs (marked in blue) and belongs to Panel 1. Hence the total count for regular studs is 2 and 3 for Panel 1 and Panel 2, respectively, while, for corner studs, the count is 1 and 0 for same panels.

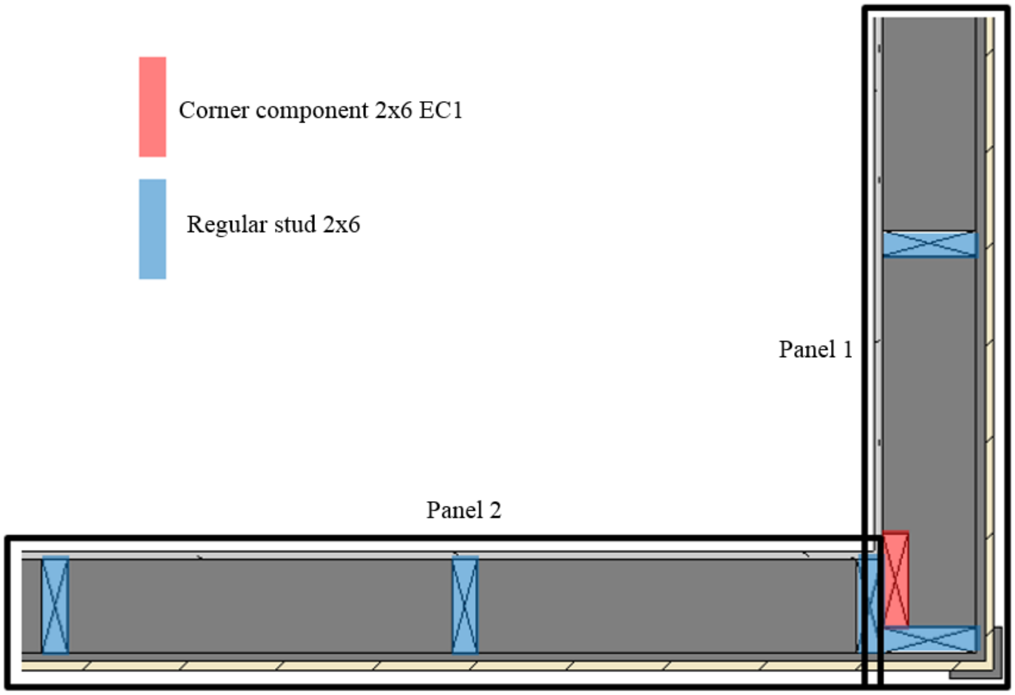


Figure 4.3 Distinction of framing components as per proposed framework

Equations (4.1.-4.5) demonstrate the application of Equations (3.4-3.12) for the total pricing of regular studs in the proposed case study followed by the pricing of a single panel. Given the proposed case study has a total of 6 exterior panels, there are 6 inputs from the BIM model to be entered into Equation 34 while the unit price provided by the cost database is \$4.00 as demonstrated in Equation 35. For the quantity of a specific panel, there is only one data entry required from the BIM model (Equation 37) while maintaining the same unit rate from the previous case. Hence, the total price for regular studs for the entire project and for Exterior Panel 1 is \$184.50 and \$45.00, respectively. The formula to estimate 2x6 regular studs is expressed below:

$$2x6Stud = f(QTO^{BIM}_{2x6Stud}) \times 2x6Stud^{Cost} (4.1)$$

$$f(QTO^{BIM}_{2x6Stud}) = \sum_{Mark} 2x6Stud^{BIM}_{Tm} = [2x6Stud^{BIM}_{E-01} \quad 2x6Stud^{BIM}_{E-02} \quad 2x6Stud^{BIM}_{E-03} \quad 2x6Stud^{BIM}_{E-04} \quad 2x6Stud^{BIM}_{E-05} \quad 2x6Stud^{BIM}_{E-06}] = [10 \quad 3 \quad 6 \quad 9 \quad 7 \quad 6] (4.2)$$

$$2x6Stud^{Cost} = \sum_{Mark} 2x6Stud^{Cost}_{Tm} = 4.50 \ (4.3)$$

$$2x6Stud = 184.50$$

For Exterior Panel 1: Mark = E-1

$$f(QTO^{BIM}_{2x6Stud}) = [2x6Stud^{BIM}_{E-1}] = [10] (4.4)$$

$$2x6Stud^{Cost} = \sum_{Mark} 2x6Stud^{Cost}_{E-1} = 4.50 \ (4.5)$$

$$2x6Stud = 45.00 \ (4.6)$$

Where:

$2x6Stud =$ the estimated cost for 2x6 studs in the project in $

$f(QTO^{BIM}_{2x6Stud})$ = the formula to extract the specific takeoff for 2x6 studs from the BIM model

$2x6Stud^{BIM}_{Tm}$ = the quantity takeoff of 2x6 studs in the project per panel (Tm) and extracted from the BIM model

$2x6Stud^{Cost}$ = the unit price of 2x6 studs in the project extracted from the cost database in $

4.1.3 Model features and results

The manufacturing department develops its model from the initial BIM model prepared by the design & drafting department. During the drafting stage, the add-on responsible for the framing model is set to configure different types of wood components in modelling software such as Autodesk Revit and ARCHICAD. Figure 4.4 demonstrates the distinction made in the studs and plates used in order to identify their function in the model used to extract the quantity of window components in the panel. It is important to note this practice is specific for the manufacturing department, since only the wall area or total length of the framing components is sufficient information for the stick-built practice. Some adjustments are needed in the framing model provided by the framing add-on in order to adapt the naming conventions described in the Methodology chapter and extract the information required by the design & drafting department. After these modifications are set, the model is reviewed and used for takeoff.

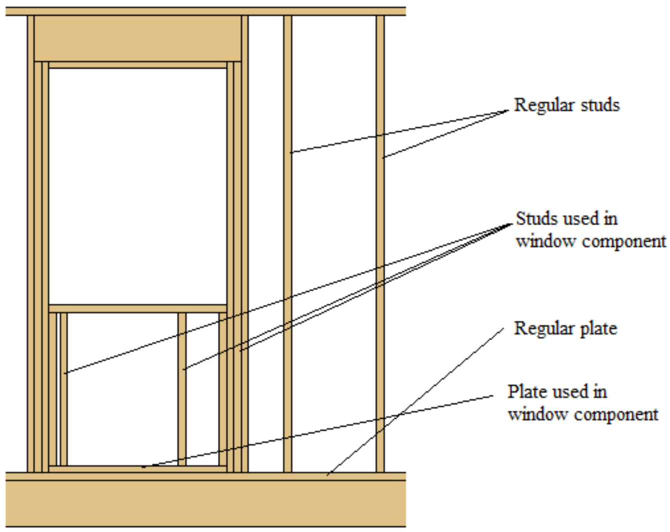
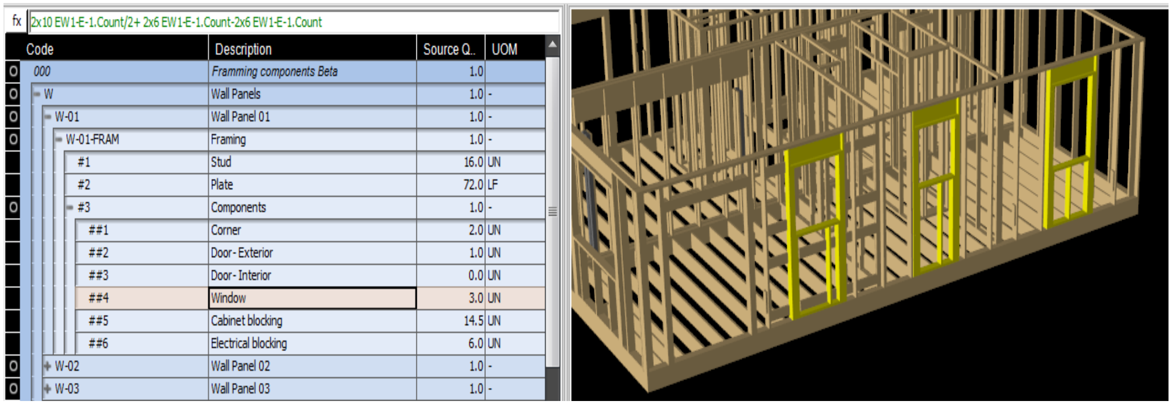


Figure 4.4 Modelling wood frame components according to its function

Modelling software, such as Autodesk Revit and Gaphisoft's ARCHICAD, are not capable of providing this type of takeoff, so other software, such as Vico Software, is used to manage and provide specific takeoffs for the manufacturing process. These takeoffs are extracted through formulas dependent on pre-modelled elements, so extra graphic detailing may be required. Figure 4.5 demonstrates the takeoff of framing components in a wall panel and the highlighting of the window components in the same panel. This work allows acquisition of the required information to perform the project coordination with other consultant designs with no extra detailing in the BIM model required. Hence it can be concluded that there is no need for achieving an LOD of 400 in the case of off-site construction manufacturing.



fx 2x10 EW1-E-1.Count/2+ 2x6 EW1-E-1.Count-2x6 EW1-E-1.Count

Code	Description	Source Q..	UOM
000	*Framming components Beta*	1.0	
W	Wall Panels	1.0	-
W-01	Wall Panel 01	1.0	-
W-01-FRAM	Framing	1.0	-
#1	Stud	16.0	UN
#2	Plate	72.0	LF
#3	Components	1.0	-
##1	Corner	2.0	UN
##2	Door - Exterior	1.0	UN
##3	Door - Interior	0.0	UN
##4	Window	3.0	UN
##5	Cabinet blocking	14.5	UN
##6	Electrical blocking	6.0	UN
W-02	Wall Panel 02	1.0	-
W-03	Wall Panel 03	1.0	-

Figure 4.5 Example of detailed takeoff with LOD 350 model

4.2 Second case study

The second application of the (i^3) concept consists of a residential 4-storey building with 84 residential apartments (21 per floor) with 13 types of units built by Landmark Group of Builders in Edmonton, AB. The purpose of this case study is to provide Landmark's management team with a more efficient cost estimation and tendering process through the application of BIM. The project used in this case study has a common typology for its scope with a cast-in-place concrete substructure,wood frame suprastructure (as demonstrated in Figure 4.6), and a similar layout (as shown in Figure 4.7) for its overall clientele. As general contractors, tasks and services are allocated in scopes of work, estimated, and placed to tender to available subcontractors (e.g., concrete formwork, carpentry labour, supply and install of flooring, etc.). This method is commonly adopted by this industry regardless of the project's size, typology, or use (residential, commercial, etc.), hence indicating an opportunity for this framework to be applied in a wide range of cases with a high level of success.

Figure 4.6 3D overview of second case study

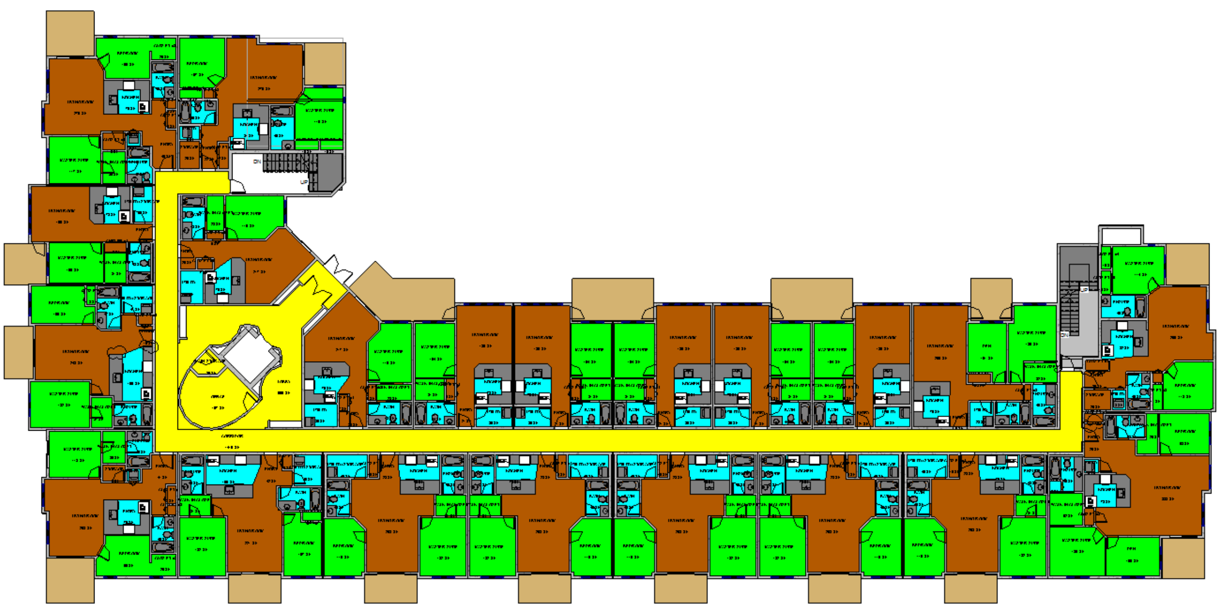


Figure 4.7 Main floor plan of second case study

4.2.1 Discussion about the BIM model progression

Taking into consideration the stakeholder requirements and the nature of research work already carried out, it was decided to extract the data from the information already provided by the consultants in the drawings and avoid extra detailing as opposed to the previous case study.

Instead of performing the actual work, Landmark is the general contractor thus does not necessarily need to expend the effort to acquire all information about every contract. Hence, the framework connects cost items in the 3D model at an LOD 300 since this level of information can be commonly found in the current deliverables of both the design & drafting department and the consultants. Shop drawings provided from trades (e.g., rebar detailing, kitchen cabinets, etc.) are not incorporated into the framework since this level of detailed information requires a greater level of effort than the value of its outcome, and some of the shop drawings will only be performed after the contract is awarded. As an example, rebar is not modelled in the structural model (nor is there detail in the structural drawings provided by the structural consultant). In order to price the rebar, the framework applies a ratio (kg/m3) to the volume of each type of structural element (e.g., beam, structural slab, etc.) so the total weight of every element can be priced accordingly. The estimation of this scope follows the logic demonstrated in Equations 3.22-3.31 and is performed using Equations 4.7-4.11 below. As per the equations below, rebar is priced based on the concrete volume of structural elements and a consumption factor per structural element predetermined in the cost database.

$$RebarMAT = f(QTO_{RebarMAT}^{BIM}) \times RebarMAT^{Cost} \quad (4.7)$$

$$f(QTO_{RebarMAT}^{BIM}) \equiv C_{Element}^{Cost} \times f(QTO_{ConcreteMAT}^{BIM}) \quad (4.8)$$

$$f(QTO_{RebarMAT}^{BIM}) = \left[C_{Beam}^{BIM} \times \sum_1^n Beam_i^{BIM} + C_{Pad}^{BIM} \times \sum_1^n Pad_i^{BIM} + C_{Column}^{BIM} \times \sum_1^n Column_i^{BIM} + C_{Spread}^{BIM} \times \sum_1^n Spread_i^{BIM} + C_{SOG}^{BIM} \times \sum_1^n SOG_i^{BIM} + C_{Slab}^{BIM} \times \sum_1^n Slab_i^{BIM}\right] = \begin{bmatrix}100 \times 221.32 & 100 \times 176.41 & 120 \times 16.75 & 100 \times 35.98 & 80 \times 243.17 & 70 \times 352.89\end{bmatrix} \quad (4.9)$$

$$RebarMAT^{Cost} = [1.45] \quad (4.10)$$

$$RebarMAT = 129{,}828.51 \quad (4.11)$$

Where:

$RebarMAT =$ the estimated cost for rebar supply in the project in \$

$f(QTO_{RebarMAT}^{BIM})$ = the formula to extract the specific takeoff for rebar supply from the BIM model

$C_{Element}^{Cost}$ is the consumption of rebar per concrete volume as per structural element (Beam, Pad, Column, Spread footing, Slab on grade and Slab)

$f(QTO_{ConcreteMAT}^{BIM})$ = the formula to extract the specific takeoff for concrete supply from the BIM model

$RebarMAT^{Cost} =$ the unit price of rebar supply in the project extracted from the cost database in \$

4.2.2 Cost breakdown structure

This section demonstrates the relationship between the estimation document and the BIM model by organizing its breakdown structure accordingly. The estimation has a total of five levels, of which its macro levels are displayed in Table 4.5 with their respective codes, descriptions, and methods to acquire each takeoff. The hard cost item is the most extensive and time-consuming item to be estimated; hence it is the main target of this framework, and the part which is being directly linked to the BIM model. Soft cost, land present value, and overhead are easily estimated due to the default quantity of one (the user may only pay for one building permit or architectural service), while contingency is estimated as a percentage value of hard and soft cost, respectively.

Table 4.3 Macro levels in presented case study

Code	Cost item	Description	Takeoff practice
1	Hard cost	Tangible construction cost such as concrete work, wood framing, and flooring	BIM-automated
2	Soft cost	Cost regarding services not directly related to the hard cost (e.g., consultant fees, buildint permits, etc.)	Takeoff of one
3	Contingency	Cost created in order to account for uncertainties in the project	Percentage from hard and soft cost
4	Land present value	Land value at the moment of investment	Takeoff of one
5	Overhead	Expense created to address indirect cost such as office expenses and administrative cost	Takeoff of one

Since hard cost is the main target of this framework, it will be discussed in more detail in this section. It is the most time consuming and error-prone item of the estimation and it is connected to the BIM model for this same reason. The hard cost section contains four extra levels due to the level of detail required from the management team according to the information present in the drawings. Table 4.4 displays a part of the painting contract breakdown, which includes its organization in reference to the codes, and its respective levels. The first level has two options: (1) base building, which is shown in Table 4.6, and (2) finishes, which is not shown, but separates the tasks applied to the entire building and its finishes, respectively. The second level depicts the scope name to be tendered (48 in total); the third level is responsible for grouping the main items in the contract while the fourth level consists of the actual cost items to be connected to the takeoffs provided by the BIM model. The Key Codes of the first and second levels follow the codes provided by the company while the third and fourth levels are taken or adapted from the Masterformat. The key code of the fourth level in particular consists merely of an extension from its summary item in the third level as can be seen in Table 4.6. Masterformat codes are allocated on the lowest levels of the breakdown structure so, when generating sales and financial departments, the items are easily reorganized by the Masterformat divisions (e.g., concrete, wood, openings, etc.) rather than the current organization by contracts to be tendered. The complete estimation according to its contracts for this case study, including the rest of the parameters, presented in Table 4.6, can be found in Appendix B of this thesis.

Table 4.4 Paint contract as per estimated in the framework

Level	Key Code	Description
1	BB	Base Building
2	CC1-79-9100	Paint
3	79-9101	Wall
4	79-9101.01	Retaining
4	79-9101.02	Interior
4	79-9101.03	Stair
4	79-9101.04	Lobby
4	79-9101.05	Corridor
3	79-9102	Ceiling
4	79-9102.01	Retaining
4	79-9102.02	Remaining spaces

Equations (4.12-4.14) demonstrates the estimation for the painting scope on this case study, by demonstrating the different unit prices applied to the different Fi on this project. It also demonstrates how the price in breakdown allowing PMO to better assess opportunities for savings and payment progression through the project.

$$Paint = f(QTO_{Paint}^{BIM}) \times Paint^{Cost} \quad (4.12)$$

$$f(QTO_{Paint}^{BIM}) = [\sum_1^n Corridor_i^{BIM} + \sum_1^n Interior_i^{BIM} + \sum_1^n Stair_i^{BIM} + \sum_1^n Lobby_i^{BIM} + \sum_1^n Retaining_i^{BIM} + \sum_1^n CeilingRetaining_i^{BIM} + \sum_1^n CeilingRemaining_i^{BIM}] = [17941 \quad 112689 \quad 4564 \quad 1281 \quad 10745 \quad 19822 \quad 59887] \quad (4.13)$$

$$Paint^{Cost} = \begin{bmatrix} Corridor^{Cost} \\ Interior^{Cost} \\ Stair^{Cost} \\ Lobby^{Cost} \\ Retaining^{Cost} \\ CeilingRetaining^{Cost} \\ CeilingRemaining^{Cost} \end{bmatrix} = \begin{bmatrix} 0.90 \\ 0.75 \\ 0.90 \\ 1.00 \\ 0.25 \\ 0.25 \\ 0.60 \end{bmatrix} \quad (4.14)$$

$$Paint = 149{,}626.20$$

4.2.3 Model features and results

As mentioned previously, the parametric estimation model (hard cost) is divided by the scopes of work according to each contract, and is tendered throughout the project with its cost items connected to codes extracted from the Masterformat standard in order to satisfy other departments' needs. Moreover, planners and managers need the takeoffs and cost at different levels of detail depending on the situation and the stakeholders involved in the discussion. The detailed breakdown of every contract is presented in Appendix B.

Furthermore, the framework is able to provide a high level of automation for the estimation process; as demonstrated in Figure 4.8 below, the framework is able to provide an 88% automation level (automated + semi-automated items) for the case study, showing a concise automation level with its first application. Automated items correspond to activities such as drywall, concrete formwork, etc., and semi-automated items are assigned to items with predetermined quantities of one (e.g., building permits and land value), while the remaining manual takeoffs are items which required too great a modelling effort to acquire the information, or there was no information available from the cost perspective. Moreover, the framework provides an increase in detailing of information meeting the requirements from the Engineering department by delivering Class 2 estimation in approximately two days, rather than the current Class 3 estimation, which requires approximately three weeks to be finalized.

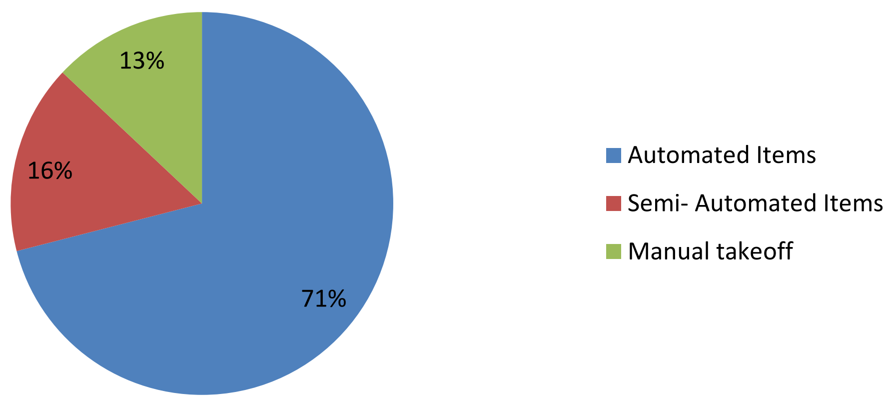


Figure 4.8 Automation level of cost items

In order to accommodate the requirements from the design & drafting department, the MEP BIM models are developed by the author in this pilot study, based on the drawings provided by consultants, in order to demonstrate the advantages of this technology to the project coordination process following the procedures previously mentioned in the Methodology chapter. Figure 4.9 demonstrates a plumbing detail from a typical suite modelled on a 400 LOD; after which, it has been decided that a 350 LOD shall suffice since MEP subtrades do not provide the level of cost information required to match the BIM model details.

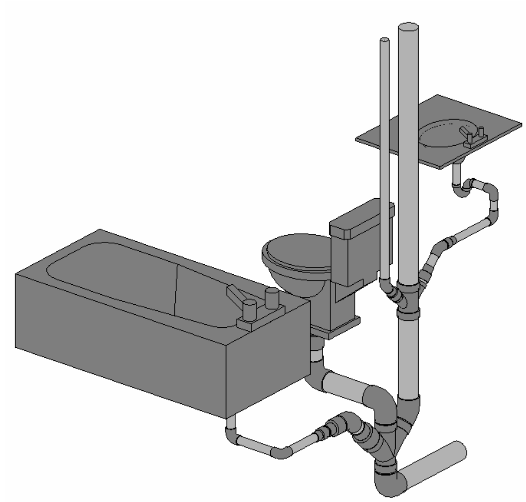


Figure 4.9 Plumbing detail on pilot study

In order to enhance the project coordination process with the consultants, visibility parameters are developed based on the pre-configured settings defined in the BIM Manual presented to the company , and as demonstrated in Figure 4.10. The process of colour-coding elements by consultant may not seem efficient; however, it guarantees clear communication and avoids confusion between all stakeholders involved during the coordination process as displayed in Figure 4.11. Furthermore, a clash detection analysis is performed with Autodesk Navisworks in order to detect interferences between elements and avoid rework on-site.

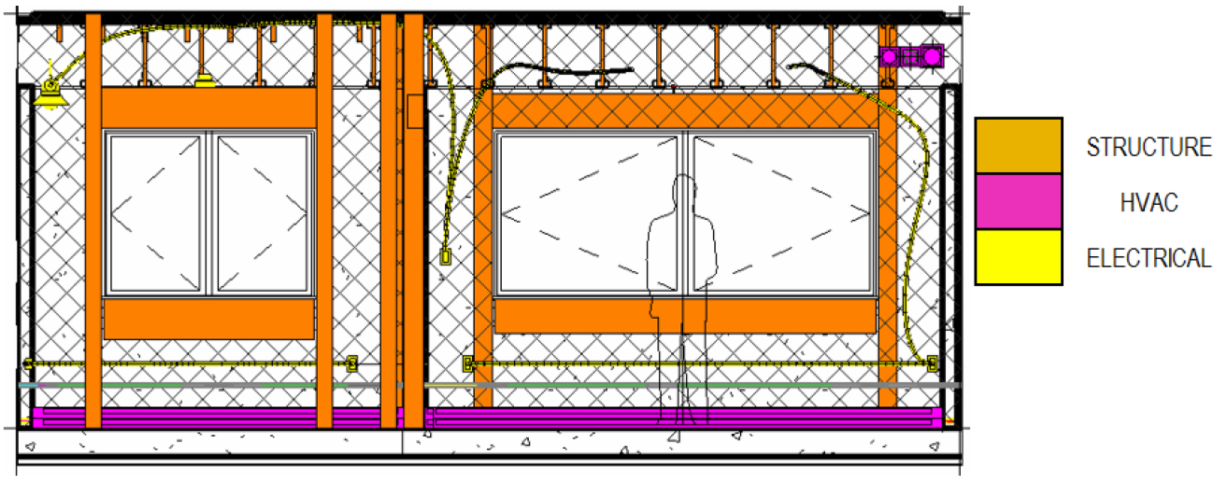


Figure 4.10 Customized view for project coordination

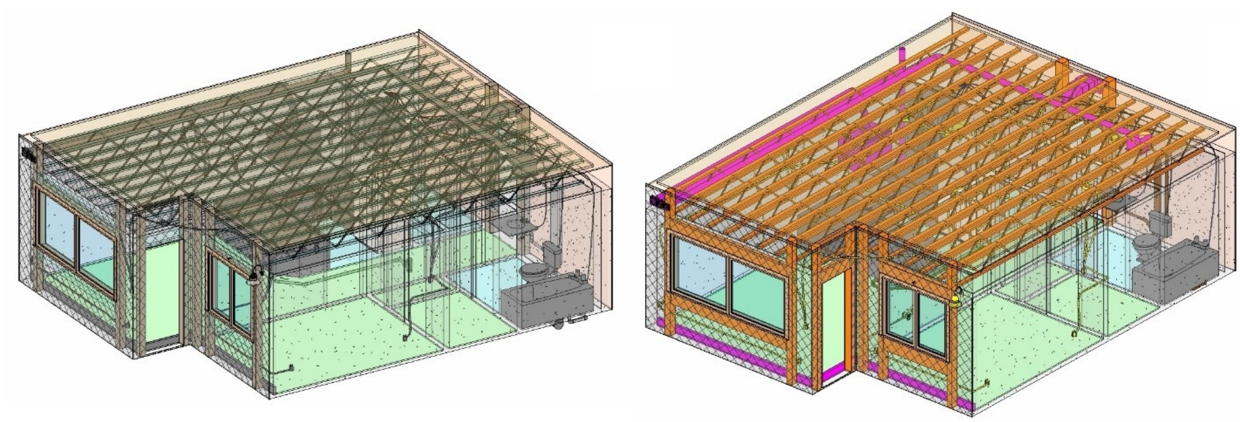


Figure 4.11 Result of customized sets for project coordination

CHAPTER 5 CONCLUSION

5.1 General Conclusions

This research has performed a full study on the needs of stakeholders in reference to the use of BIM technology in the manufacturing process, taking into consideration the various contexts and requirements of different parties involved in the process. By incorporating the (i^3) concept into two case studies, this study has accomplished a method of comprehending all information by adding intelligence to the project management process through the implementation of the BIM model as a hub of information which is available to all parties. In this research, the first application of the (i^3) concept has identified the need for adaptations of BIM software to the modular construction industry, and has also achieved a high level of detail in drafting and cost estimation thereby allowing the manufacturing plant to price and forecast its inventory needs according to its demand for projects. For the second application of the (i^3) concept, the author has adequately managed the needs of the stakeholders for general contracting by adapting current practices in a format that allows the automation of procedures by the BIM model. Moreover, this research has succeeded in quantifying the level of detail required to work with this technology as well as metrics to monitor its enhancements provided by the developed framework.

5.2 Research Contribution

The developed framework can benefit academia and industry regarding BIM implementation for off-site construction and general contracting, extending its range to a significant portion of the construction industry. The benefits are described below:

- Application of the (i^3) concept for implementation of BIM tools by performing a comprehensive analysis of the current practice in the industry, accommodating the information available, and adding the intelligence required in order to enhance the traditional workflow.

- Use of ontology in order to implement the collaborative use of BIM among several stakeholders for construction manufacturing and general contracting practices.
- Integration of manufacturing expertise in the early stages of design and planning phases by incorporating specific purpose takeoffs such as wall assemblies into the cost breakdown, thus bringing a more comprehensive effect of changes throughout the design process.
- Significant reduction of non value-added activities, such as quantity takeoff, by almost 90% for cost items while providing more detailed information (Class 3 to Class 2), investing less than 15% of the time traditionally required as a result (two days instead of three working weeks).
- Correlation of metrics to evaluate deliverables through the design and planning phases, and a comprehensive mapping of the progression and final detail of the BIM model for modular construction and general contracting.

5.3 Research Limitations

The research limitations are as follows:

- As the process of retrieving data from the cost database and relating it to the BIM model is still carried out manually, real-time cost synchronizations are still not possible in the present work.

- The information provided by different departments (stakeholders) still do not carry the same level of detail (e.g., electrical and mechanical trades) since subcontractors are not used to (i) providing this level of information, (ii) using the BIM model during the tendering process, or (iii) the transparency propagated by BIM culture.

- Naming conventions, despite being fully functional with the cost estimation model connection, are sensitive to any change, thus jeopardizing the connection and consequently the estimation accuracy.

5.4 Future Improvements

This research provides a comprehensive study of the use and implementation of BIM in modular construction and its applications in data integration for project management in general contracting. Future improvements are described below:

- Enhancement of software applications with an emphasis on the BIM-based structural framing models to consider the necessary requirements for the modular construction industry.

- Development of a framework to assist in acquiring cost through labour measurements and use of target cost by considering the BIM model as a hub of information for subcontractors and modular construction practitioners.

- Use of ontology-based semantics in order to identify the inter-relationships between building elements, and acquire relevant information such as project documentation, quantity takeoff, and decision-making criteria to improve project management performance.

- Incorporation of procedures and development of software applications in order to ensure the connection between the BIM and cost models for reliance of the automation during the cost estimation process.

- Integration of other information into the proposed framework such as carbon dioxide emissions and embodied energy of materials as construction process for a multi-criteria decision process taken into account cost and non-cost related perspectives.

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CHAPTER 7 APPENDICES

APPENDIX A

Key Code	Description	Formula	Unit
W	Wall Panels		
WE	Exterior Walls		
WE-01	Exterior Wall Panel 01		
WE-01-WFRA	Framing		
WFRA-#01	2X6 Stud	2x6-E-1.Count	UN
WFRA-#02	2x4 Stud	2x4-E-1.Count	UN
WFRA-#03	2x6 Plate	2x6p-E-1.Count	UN
WFRA-#04	2x4 Plate	2x4p-E-1.Count	UN
WFRA-#05	Mid. Height Backing	2x6 CB-E-1.Count	UN
WFRA-#06	7/16" Sheating	0	UN
WFRA-#07	15/32" Sheating	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area/32	UN
WFRA-#08	2 3/4" Nail (Sheating)	(EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area/32)*40	UN
WFRA-#09	3" Nail (Plate to Plate)	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area	UN
WFRA-#10	3 3/4" Nail (Plate to Stud)	SUM(2x6 EC1-E-1.Count, 2x6 CB-E-1.Count, 2x6 ED1-E-1.Count, 2x6 EI1-E-1.Count, 2x6 EI2-E-1.Count, 2x6 EW1-E-1.Count, 2x6-E-1.Count)	UN
WFRA-#11	Component	1	
WFRA-#11-#001	Corner Component	2x6 EC1-E-1.Count	UN
WFRA-#11-#002	Door- Exterior Component 1	(2x6 ED1-E-1.Count/14+ 2x6 EDp1-E-1.Count/3)/2	UN
WFRA-#11-#003	Door- Interior Component	0	UN
WFRA-#11-#004	Window Component 1	(2x10 EW1-E-1.Count/3 + 2x6 EW1-E-1.Count/10 + 2x6 EWp1-E-1.Count/3)/3	UN
WFRA-#11-#005	Cabinet blocking Component	2x6 CB-E-1.Count	UN
WFRA-#11-#006	Electrical blocking Component	2x4 EB-E-1.Count	UN
WFRA-#11-#007	Intersection 1	2x6 EI1-E-1.Count	UN
WFRA-#11-#008	Intersection 2	2x4 EI2-E-1.Count	UN
WE-01-EWAL	Substrate		
EWAL-#01	Siding - Clapboard	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area	SF
EWAL-#02	Building Wrap	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area/(9*150)	UN
EWAL-#04	Rigid Insulation 1 1/4"	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area	UN
EWAL-#05	Poly	EXTERIOR-INTERIOR-E-1.Net Reference Side Surface Area	UN

WE-01-DRYW	Drywall		
DRYW-#01	Drywall 1/2"	EXTERIOR-INTERIOR-E-1.Net Opposite Reference Side Surface Area/(4*8)	UN
DRYW-#02	Drywall 1/2" Water Resistant	EXTERIOR-INTERIOR2-E-1.Net Opposite Reference Side Surface Area/(4*8)	UN
DRYW-#03	Prime Coat	EXTERIOR-INTERIOR-E-1.Net Opposite Reference Side Surface Area	SF
DRYW-#04	Paint	EXTERIOR-INTERIOR-E-1.Net Opposite Reference Side Surface Area	SF
WE-01-WOPE	Openings		
OPEN-#01	Windows		
OPEN-#01-#001	Window 1	W1-E-1.Count	UN
OPEN-#01-#002	Window 2	W2-E-1.Count	UN
OPEN-#01-#003	Window 3	W3-E-1.Count	UN
OPEN-#01-#004	Window 4	W4-E-1.Count	UN
OPEN-#01-#005	Window 5	W5-E-1.Count	UN
OPEN-#02	Doors		
OPEN-#02-#001	Exterior door 1	DE1-E-1.Count	UN
OPEN-#02-#002	Exterior door 2	DE2-E-1.Count	UN
OPEN-#02-#003	Exterior door 3	DE3-E-1.Count	UN
OPEN-#02-#004	Interior door 1	DS1-E-1.Count	UN
OPEN-#02-#005	Interior door 2	DS2-E-1.Count	UN
OPEN-#02-#006	Interior door 3	DS3-E-1.Count	UN
OPEN-#02-#007	Pocket door 1	DB1-E-1.Count	UN
OPEN-#02-#008	Pocket door 2	DB2-E-1.Count	UN
OPEN-#02-#009	Pocket door 3	DB3-E-1.Count	UN
WP	Partition Walls		
WP-01	Partition Wall Panel 01		
WP-01-WFRA	Framing		
WFRA-#01	2X6 Stud	2x6-C-1.Count	UN
WFRA-#02	2x4 Stud	2x4-C-1.Count	UN
WFRA-#03	2x6 Plate	2x6p-C-1.Count	UN
WFRA-#04	2x4 Plate	2x4p-C-1.Count	UN
WFRA-#05	Mid. Height Backing	2x6 CB-C-1.Count	UN
WFRA-#06	7/16" Sheating	0	UN
WFRA-#07	15/32" Sheating	EXTERIOR-INTERIOR-C-1.Net Reference Side Surface Area/32	UN
WFRA-#08	2 3/4" Nail (Sheating)	(EXTERIOR-INTERIOR-C-1.Net Reference Side Surface Area/32)*40	UN
WFRA-#09	3" Nail (Plate to Plate)	EXTERIOR-INTERIOR-C-1.Lenght*3	UN
WFRA-#10	3 3/4" Nail (Plate to Stud)	SUM(2x6 EC1-C-1.Count, 2x6 CB-C-1.Count, 2x6 ED1-C-1.Count, 2x6 EI1-C-1.Count, 2x6 EI2-C-1.Count, 2x6 EW1-C-1.Count, 2x6-C-1.Count)	UN

WFRA-#11	Component		
WFRA-#11-#001	Corner Component	2x6 EC1-C-1.Count	UN
WFRA-#11-#002	Door- Exterior Component 1	(2x6 ED1-C-1.Count/14+ 2x6 EDp1-C-1.Count/3)/2	UN
WFRA-#11-#003	Door- Interior Component	0	UN
WFRA-#11-#004	Window Component 1	(2x10 EW1-C-1.Count/3 + 2x6 EW1-C-1.Count/10 + 2x6 EWp1-C-1.Count/3)/3	UN
WFRA-#11-#005	Cabinet blocking Component	2x6 CB-C-1.Count	UN
WFRA-#11-#006	Electrical blocking Component	2x4 EB-C-1.Count	UN
WFRA-#11-#007	Intersection 1	2x6 EI1-C-1.Count	UN
WFRA-#11-#008	Intersection 2	2x4 EI2-C-1.Count	UN
WP-01-EWAL	Substrate		
EWAL-#01	Siding - Clapboard	PARTITION-INTERIOR-C-1.Net Reference Side Surface Area	SF
EWAL-#02	Building Wrap	PARTITION-INTERIOR-C-1.Net Reference Side Surface Area/(9*150)	UN
EWAL-#03	Sheating 15/32"	0	UN
EWAL-#04	Rigid Insulation 1 1/4"	0	UN
EWAL-#05	Poly	PARTITION-INTERIOR-C-1.Net Reference Side Surface Area	UN
WP-01-DRYW	Drywall		
DRYW-#01	Drywall 1/2"	PARTITION-INTERIOR-C-1.Net Opposite Reference Side Surface Area/(4*8)	UN
DRYW-#02	Drywall 1/2" Water Resistant	PARTITION-INTERIOR2-C-1.Net Opposite Reference Side Surface Area/(4*8)	UN
DRYW-#03	Prime Coat	PARTITION-INTERIOR-C-1.Net Opposite Reference Side Surface Area	SF
DRYW-#04	Paint	PARTITION-INTERIOR-C-1.Net Opposite Reference Side Surface Area	SF
WP-01-WOPE	Openings		
OPEN-#01	Windows		
OPEN-#01-#001	Window 1	W1-C-1.Count	UN
OPEN-#01-#002	Window 2	W2-C-1.Count	UN
OPEN-#01-#003	Window 3	W3-C-1.Count	UN
OPEN-#01-#004	Window 4	W4-C-1.Count	UN
OPEN-#01-#005	Window 5	W5-C-1.Count	UN
OPEN-#02	Doors		
OPEN-#02-#001	Exterior door 1	DE1-C-1.Count	UN
OPEN-#02-#002	Exterior door 2	DE2-C-1.Count	UN
OPEN-#02-#003	Exterior door 3	DE3-C-1.Count	UN
OPEN-#02-#004	Interior door 1	DS1-C-1.Count	UN
OPEN-#02-#005	Interior door 2	DS2-C-1.Count	UN
OPEN-#02-#006	Interior door 3	DS3-C-1.Count	UN
OPEN-#02-#007	Pocket door 1	DB1-C-1.Count	UN
OPEN-#02-#008	Pocket door 2	DB2-C-1.Count	UN
OPEN-#02-#009	Pocket door 3	DB3-C-1.Count	UN

WI	Interior Walls		
WI-01	Interior Wall Panel 01		
WI-01-WFRA	Framing		
WFRA-#01	2X6 Stud	2x6-I-1.Count	UN
WFRA-#02	2x4 Stud	2x4-I-1.Count	UN
WFRA-#03	2x6 Plate	2x6p-I-1.Count	UN
WFRA-#04	2x4 Plate	2x4p-I-1.Count	UN
WFRA-#05	Mid. Height Backing	2x6 CB-I-1.Count	UN
WFRA-#06	7/16" Sheating	SUM(INTERIOR-I-1.Net Reference Side Surface Area,INTERIOR2-I-1.Net Reference Side Surface Area,MECHANICAL-I-1.Net Reference Side Surface Area)/32	UN
WFRA-#07	15/32" Sheating	0	UN
WFRA-#08	2 3/4" Nail (Sheating)	(SUM(INTERIOR-I-1.Net Reference Side Surface Area,INTERIOR2-I-1.Net Reference Side Surface Area,MECHANICAL-I-1.Net Reference Side Surface Area)/32)*(40)	UN
WFRA-#09	3" Nail (Plate to Plate)	EXTERIOR-INTERIOR-I-1.Lenght*3	UN
WFRA-#10	3 3/4" Nail (Plate to Stud)	SUM(2x6 EC1-I-1.Count, 2x6 CB-I-1.Count, 2x6 ED1-I-1.Count, 2x6 EI1-I-1.Count, 2x6 EI2-I-1.Count, 2x6 EW1-I-1.Count, 2x6-I-1.Count)*6	UN
WFRA-#11	Component		
WFRA-#11-#001	Corner Component	2x4 EC1-I-1.Count	UN
WFRA-#11-#002	Door- Exterior Component 1	0	UN
WFRA-#11-#003	Door- Exterior Component 2	0	UN
WFRA-#11-#004	Door- Interior Component	(2x10 EW1-I-1.Count/3 + 2x4 EW1-I-1.Count/10 + 2x4 EWp1-I-1.Count/3)/3	UN
WFRA-#11-#005	Window Component 1	2x4 CB-I-1.Count	UN
WFRA-#11-#006	Window Component 2	2x4 EB-I-1.Count	UN
WFRA-#11-#007	Cabinet blocking Component	2x4 EI1-I-1.Count	UN
WFRA-#11-#008	Electrical blocking Component	2x4 EI2-I-1.Count	UN
WI-01-EWAL	Substrate		
EWAL-#01	Siding - Clapboard	0	SF
EWAL-#02	Building Wrap	0	UN
EWAL-#03	Sheating 15/32"	0	UN
EWAL-#04	Rigid Insulation 1 1/4"	0	UN
EWAL-#05	Poly	0	UN
WI-01-DRYW	Drywall		
DRYW-#01	Drywall 1/2"	SUM(INTERIOR-I-1.Net Reference Side Surface Area,INTERIOR2-I-1.Net Reference Side Surface Area,MECHANICAL-I-1.Net Reference Side Surface Area)/(4*8)	UN
DRYW-#02	Drywall 1/2" Water Resistant	SUM(INTERIOR-I-1.Net Reference Side Surface Area,INTERIOR2-I-1.Net Reference Side Surface Area,MECHANICAL-I-1.Net Reference Side Surface Area)/(4*8)	UN
DRYW-#03	Prime Coat	SUM(INTERIOR-I-1.Net Reference Side Surface Area,INTERIOR2-I-1.Net Reference Side Surface Area,MECHANICAL-I-1.Net Reference Side Surface Area)	SF

APPENDIX B

Key Code	Description	Formula	Unit
BB	BASE BUILDING		
CC1-78-4000	Aluminum Ent Storefronts		-
08-1200	Main entry	Entrance.Net Reference Side Surface Area	SF
CC1-93-1216	Asphalt Paving		-
32-1200	Asphalt paving	(MANUAL)	M2
32-1140	Cement stabilization	(MANUAL)	M2
32-0500	Garage bin pad	(MANUAL)	M2
CC1-03-1100	Concrete Formwork		-
03-1100	Form & Strip Foundations - Footings		-
03-1100.01	Form & strip foundations - Grade beams GB1	SUM(GB1.Opposite Reference Side Surface Area)	SF
03-1100.11	Form & strip foundations - Pad footings F1	F1.Edge Surface Area	SF
03-1100.12	Form & strip foundations - Pad footings F2	F2.Edge Surface Area	SF
03-1100.13	Form & strip foundations - Pad footings F3	F3.Edge Surface Area	SF
03-1100.14	Form & strip foundations - Pad footings F4	F4.Edge Surface Area	SF
03-1100.21	Form & strip foundations - Pile cap P1	CP1.Edge Surface Area	SF
03-1100.41	Form & strip foundations - Foundation slab SF 1	FS 1.Edge Surface Area	SF
03-1100.42	Form & strip foundations - Foundation slab SF 2	FS 2.Edge Surface Area	SF
03-1130	Form & Strip Walls		-
03-1130.11	Form & Strip Walls- Foundation walls	Retaining1.Net Reference Side Surface Area	SF
03-1200	Form & Strip Elevated Concrete		-
03-1200.01	Form & strip- Main floor slab	SUM(Concrete 1.Net Bottom Surface Area, Concrete 2.Net Bottom Surface Area, Concrete 3.Net Bottom Surface Area)	SF
03-1200.11	Form & strip- Concrete beam BC1	BC1.Opposite Reference Side Surface Area +BC1.Reference Side Surface Area	SF
03-1200.12	Form & strip- Concrete beam BC2	BC2.Opposite Reference Side Surface Area +BC2.Reference Side Surface Area	SF
03-1200.13	Form & strip- Concrete beam BC3	BC3.Opposite Reference Side Surface Area +BC3.Reference Side Surface Area	SF
03-1200.14	Form & strip- Concrete beam BC4	BC4.Opposite Reference Side Surface Area +BC4.Reference Side Surface Area	SF
03-1200.15	Form & strip- Concrete beam BC5	BC5.Opposite Reference Side Surface Area +BC5.Reference Side Surface Area	SF
03-1200.16	Form & strip- Concrete beam BC6	BC6.Opposite Reference Side Surface Area +BC6.Reference Side Surface Area	SF
03-1200.17	Form & strip- Concrete beam BC7	BC7.Opposite Reference Side Surface Area +BC7.Reference Side Surface Area	SF
03-1200.18	Form & strip- Concrete beam BC8	BC8.Opposite Reference Side Surface Area +BC8.Reference Side Surface Area	SF
03-1300	Form & Strip Misc. Concrete		-
03-1300.01	Form & strip-Concrete column CC1	CC1.Vertical Surface Area	SF

CC1-03-2000	Concrete Reinforcement Supply		-
03-2000.01	Concrete reinforcement supply-Grade beams	SUM(GB1.Gross Volume)	KG
03-2000.11	Concrete reinforcement supply-Pad footings	SUM(FP1.Net Volume+ FP2.Net Volume+ FP3.Net Volume+ FP4.Net Volume+ FS 1.Net Volume+ FS 2.Net Volume)	KG
03-2000.21	Concrete reinforcement supply-Pile caps	SUM(CP1.Gross Volume)	KG
03-2000.41	Concrete reinforcement supply-Foundation walls	Retaining 1.Net Volume	KG
03-2000.51	Concrete reinforcement supply-Slab on grade	SOG 1.Net Volume+ SOG 2.Net Volume	KG
03-2000.61	Concrete reinforcement supply-Main floor slab	Concrete 1.Net Volume+ Concrete 2.Net Volume+ Concrete 3.Net Volume	KG
03-2000.71	Concrete reinforcement supply-Beams	BC1.Net Volume+ BC2.Net Volume+ BC3.Net Volume+ BC4.Net Volume+ BC5.Net Volume+ BC6.Net Volume+ BC7.Net Volume+ BC8.Net Volume	KG
03-2000.81	Concrete reinforcement supply-Columns	CC1.Net Volume	KG
CC1-03-2100	Concrete Reinforcement Instalation		-
03-2100.01	Concrete reinforcement instalation-Grade beams	SUM(GB1.Gross Volume)	KG
03-2100.11	Concrete reinforcement instalation-Pad footings	SUM(FP1.Net Volume+ FP2.Net Volume+ FP3.Net Volume+ FP4.Net Volume+ FS 1.Net Volume+ FS 2.Net Volume)	KG
03-2100.21	Concrete reinforcement instalation-Pile caps	SUM(CP1.Gross Volume)	KG
03-2100.41	Concrete reinforcement instalation-Foundation walls	Retaining 1.Net Volume	KG
03-2100.51	Concrete reinforcement instalation-Slab on grade	SOG 1.Net Volume+SOG 2.Net Volume	KG
03-2100.61	Concrete reinforcement instalation-Main floor slab	Concrete 1.Net Volume+ Concrete 2.Net Volume+ Concrete 3.Net Volume	KG
03-2100.71	Concrete reinforcement instalation-Beams	BC1.Net Volume+ BC2.Net Volume+ BC3.Net Volume+ BC4.Net Volume+ BC5.Net Volume+ BC6.Net Volume+ BC7.Net Volume+ BC8.Net Volume	KG
03-2100.81	Concrete reinforcement instalation-Columns	CC1.Net Volume	KG
CC1-03-3000	Cast-In-Place Concrete		-
03-3000.01	Concrete placing-Grade beams	GB1.Top Surface Area	SF
03-3000.11	Concrete placing-Isolated footings	SUM(FP1.Net Top Surface Area, FP2.Net Top Surface Area, FP3.Net Top Surface Area, FP4.Net Top Surface Area)	SF
03-3000.21	Concrete placing-Pile caps	CP1.Net Top Surface Area	SF
03-3000.41	Concrete placing-Foundations walls	Retaining.Net Volume	M3
03-3000.51	Concrete placing-Slab on grade	SUM(SOG 1.Net Top Surface Area, SOG 2.Net Top Surface Area)	SF
03-3000.61	Concrete placing-Elevated concrete	SUM(Concrete 1.Net Bottom Surface Area, Concrete 2.Net Top Surface Area, Concrete 3.Net Bottom Surface Area)+SUM(BC1.Top Surface Area, BC2.Top Surface Area, BC3.Top Surface Area, BC4.Top Surface Area, BC5.Top Surface Area, BC6.Top Surface Area, BC7.Top Surface Area, BC8.Top Surface Area)	SF
03-3000.71	Concrete placing-Columns	Concrete-Rectangular-Column-CC1.Net Volume	M3
03-3000.81	Flatwork labour- Ramp	(MANUAL)	LS
03-3000.91	Concrete pumping	(MANUAL)	LS

CC1-03-1101	Concrete Supply		-
03-1101.01	Concrete supply - Footings	FP1.Net Volume+ FP2.Net Volume+ FP3.Net Volume+ FP4.Net Volume+CP1.Net Volume+ GB1.Net Volume+ FR 1.Net Volume+ FR 2.Net Volume	M3
03-1101.02	Concrete supply - Walls	Retaining 1.Net Volume	M3
03-1101.03	Concrete supply - Piles	PC 1.Net Volume	M3
03-1101.04	Concrete supply - Stairs	Stair 1.Net Volume	M3
03-1101.05	Concrete supply - Columns	CC1.Net Volume	M3
03-1101.06	Concrete supply - Slab on grade	SOG 1.Net Volume+ SOG 2.Net Volume	M3
03-1101.07	Concrete supply - Main floor elevated slab + beams	Concrete 1.Net Volume+ Concrete 2.Net Volume+ Concrete 3.Net Volume+ BC1.Net Volume+ BC2.Net Volume+ BC3.Net Volume+ BC4.Net Volume+ BC5.Net Volume+ BC6.Net Volume+ BC7.Net Volume+ BC8.Net Volume	M3
CC1-93-1600	Curbs/Gutters/Sidewalks		-
32-1600.01	Curb	(MANUAL)	LF
32-1600.02	Concrete barrier curb	(MANUAL)	LF
32-1320	Sidewalk	(MANUAL)	SF
CC1-09-2000	Drywall		-
07-2100	Insulation		-
07-2100.01	R20 insulation for exterior walls	SUM(Exterior-Interior.Net Reference Side Surface Area, Exterior-Mechanical.Net Reference Side Surface Area,Exterior-Stairs.Net Reference Side Surface Area)	SF
07-2100.02	Double layer of R8 insulation on corridor walls	SUM(Corridor-Interior.Net Reference Side Surface Area, Corridor-Mechanical.Net Reference Side Surface Area)	SF
07-2100.03	Double layer of R12 insulation on party walls	SUM(Partition-Interior.Net Reference Side Surface Area, Partition-Mechanical.Net Reference Side Surface Area)	SF
07-2100.04	R40 blown cellulose insulation in atic	Top Floor.Net Top Surface Area	SF
07-2100.05	Corridor ceiling insulation	C Corridor.Net Top Surface Area	SF
07-2100.06	10" blown cellulose insulation in floor cavities	SUM(Carpet 1.Net Top Surface Area,Hardwood 1.Net Top Surface Area ,Tile 1.Net Top Surface Area)	SF
07-2110	Ceiling		-
07-2110.01	Textured ceiling	SUM(Appartment.Net Top Surface Area, Balcony Ceiling.Net Top Surface Area, Balcony Ceiling 2.Net Top Surface Area, Corridor.Net Top Surface Area, Utilities.Net Top Surface Area,Lobby.Net Top Surface Area)	SF
09-2800	Boarding		-
09-2800.01	Double layer of 5/8" Typex on ceilings	SUM(Appartment.Net Top Surface Area, Corridor.Net Top Surface Area, Lobby.Net Top Surface Area, Utilities.Net Top Surface Area)	SF
09-2800.02	5/8" Typex drywall on corridor ceiling	SUM(Appartment.Net Top Surface Area, Corridor.Net Top Surface Area, Lobby.Net Top Surface Area, Utilities.Net Top Surface Area)*1	SF

09-2800.03	5/8" Typex drywall on exterior walls	SUM(Exterior-Interior.Net Opposite Reference Side Surface Area, Exterior-Mechanical.Net Opposite Reference Side Surface Area)	SF
09-2800.04	5/8" Typex drywall on party walls	SUM(Partition-Interior.Net Reference Side Surface Area, Partition-Interior.Net Opposite Reference Side Surface Area, Partition-Mechanical.Net Reference Side Surface Area, Partition-Mechanical.Net Opposite Reference Side Surface Area)	SF
09-2800.05	Double layer of 5/8" Typex on corridor walls	SUM(Corridor-Interior.Net Reference Side Surface Area, Corridor-Mechanical.Net Reference Side Surface Area)	SF
09-2800.06	5/8" Typex drywall on suite walls in corridor	SUM(Corridor-Interior.Net Opposite Reference Side Surface Area, Corridor-Mechanical.Net Opposite Reference Side Surface Area)	SF
09-2800.07	1/2" STD drywall on interior partitions	SUM(Interior1.Net Reference Side Surface Area, Interior1.Net Opposite Reference Side Surface Area, Interior2.Net Reference Side Surface Area, Interior2.Net Opposite Reference Side Surface Area)	SF
CC1-26-0500	Electrical	1	-
26-0500	Electrical	(MANUAL)	SF
CC1-14-2000	Elevator	1	-
14-2000	Elevator	(MANUAL)	EA
CC1-06-0573	Fire Retardant Treatment	1	-
06-0570.01	ProTEK onsite application	SUM(Carpet 1.Net Top Surface Area,Hardwood 1.Net Top Surface Area ,Tile 1.Net Top Surface Area)	SF
06-0570.02	AtTEK pretreratment	SUM(Concrete 1.Net Top Surface Area, Concrete 2.Net Top Surface Area, Concrete 3.Net Top Surface Area)	SF
CC1-06-1733	Floor Joist/Trusses	1	-
06-1730	Structural wood floors	(MANUAL)	SF
CC1-79-6500	Flooring Common Area	1	-
09-6000.01	Lobby wall finishing	SUM(Corridor-Lobby.Net Opposite Reference Side Surface Area ,Lobby.Net Opposite Reference Side Surface Area ,Lobby-Elevator.Net Reference Side Surface Area, Lobby-Interior.Net Reference Side Surface Area ,Lobby-Mailbox.Net Reference Side Surface Area, Lobby-Mechanical.Net Reference Side Surface Area ,Lobby-Utilities.Net Reference Side Surface Area)	SF
09-6000.02	Lobby floor finishing	Carpet 2.Net Bottom Surface Area	SF
09-6000.03	Flooring amenities (Elec, Mec)	Vinyl 1.Net Top Surface Area	SF
09-6000.04	Flooring corridor and stairs	Carpet 2.Net Top Surface Area	SF
09-6000.05	Wall covering- Rubber base	SUM(Corridor-Interior.Length, Corridor-Mechanical.Length)	LF
09-6000.03	Flooring amenities (Elec, Mec)	Vinyl 1.Net Top Surface Area	SF
CC1-06-1100	Framing Labour	1	-
06-1110	Frame	SUM(Balcony-Interior.Net Reference Side Surface Area, Corridor-Interior.Net Reference Side Surface Area, Corridor-Lobby.Net Reference Side Surface Area, Corridor-Mailbox.Net Reference Side Surface Area, Corridor-Mechanical.Net Reference Side Surface Area ,Elevator.Net Reference Side Surface Area*2, Entrance.Net Reference Side Surface Area, Entrance-Mechanical.Net Reference Side Surface Area, Exterior-Interior.Net Reference Side Surface Area, Exterior-Mechanical.Net Reference Side Surface Area, Exterior-Stairs.Net Reference Side Surface Area, Interior1.Net Reference Side Surface Area, Interior1.Net Reference Side Surface Area, Lobby-Elevator.Net Reference Side Surface Area,	SF

		Lobby-Interior.Net Reference Side Surface Area, Lobby-Mailbox.Net Reference Side Surface Area, Lobby-Mechanical.Net Reference Side Surface Area, Lobby-Utilities.Net Reference Side Surface Area, Mechanical-Interior.Net Reference Side Surface Area, Partition-Interior.Net Reference Side Surface Area, Partition-Mechanical.Net Reference Side Surface Area, Stair-Interior.Net Reference Side Surface Area, Utilities.Net Reference Side Surface Area, Utilities-Elevator.Net Reference Side Surface Area)	
06-1500	Balcony	Balcony.Count	UN
06-1100	Columns	CW 3.Count	EA
CC1-06-1100	Framing Labour	1	-
CC1-03-5400	Gypcrete		-
03-5400.01	Gypcrete- Supply	SUM(Gypcrete 1.Net Top Surface Area)	SF
03-5400.02	Gypcrete- Labour	SUM(Gypcrete 1.Net Top Surface Area)	SF
CC1-08-1113	HMD/PSF		-
08-1100	HMD/PSF- Supply and instalation	HMD.Count	EA
CC1-93-9000	Landscaping		-
32-9000.01	Landscaping - Large Rock/Boulders	(MANUAL)	LS
32-9000.02	Landscaping - mulch/fabric	(MANUAL)	SF
32-9000.03	Landscaping - Shrubs	(MANUAL)	EA
32-9000.04	Landscaping - Trees	(MANUAL)	EA
32-9000.05	Landscaping maintenance - 2years	(MANUAL)	SF
CC1-10-5523	Mail Boxes		-
10-5523	Mailboxes	(MANUAL)	LS
CC1-04-2200	Masonry		-
04-2200	Masonry tile 1	Exterior3.Net Reference Side Surface Area	SF
CC1-22-0500	Mechanical		-
23-0500	HVAC	(MANUAL)	SF
22-0500	Plumbing	(MANUAL)	SF
21-1000	Sprinkler	(MANUAL)	SF
22-4000	Fixtures	(MANUAL)	SF
21-0500	Thermal insulation & firecaulking	(MANUAL)	SF
23-0900	Controls	(MANUAL)	SF
CC1-71-2126	Misc Specialities	1	-
71-2126	Bike Rack	(MANUAL)	LS
CC1-78-3600	Overhead Door	1	-
78-3600	Overhead Door	DO 1.Count	EA
CC1-79-9100	Painting	1	-
79-9101	Wall		-
79-9101.01	Retaining	Retaining 1.Net Reference Side Surface Area	SF
79-9101.02	Interior	SUM(Balcony-Interior.Net Reference Side Surface Area, Corridor-Interior.Net Reference Side Surface Area, Interior1.Net Reference Side Surface Area*2,Mechanical-Interior.Net Reference Side Surface Area, Partition-Interior.Net Reference Side Surface Area, Partition-Mechanical.Net Reference	SF

		Side Surface Area)	
79-9101.03	Stair	SUM(Stair-Interior.Net Reference Side Surface Area,Exterior-Stairs.Net Reference Side Surface Area)	SF
79-9101.04	Lobby	SUM(Corridor-Lobby.Net Reference Side Surface Area,Lobby-Elevator.Net Reference Side Surface Area, Lobby-Interior.Net Reference Side Surface Area, Lobby-Mailbox.Net Reference Side Surface Area, Lobby-Mechanical.Net Reference Side Surface Area, Lobby-Utilities.Net Reference Side Surface Area)	SF
79-9101.05	Corridor	SUM(Corridor-Interior.Net Reference Side Surface Area, Corridor-Lobby.Net Reference Side Surface Area, Corridor-Mailbox.Net Reference Side Surface Area, Corridor-Mechanical.Net Reference Side Surface Area,Lobby-Mechanical.Net Reference Side Surface Area, Lobby-Utilities.Net Reference Side Surface Area)	SF
CC1-93-3200	Retaining Walls	1	-
32-3200	Retaining Walls	Retaining 2.Net Reference Side Surface Area	SF
CC1-06-1753	Roof Trusses	1	-
06-1740	Engineered Roof System- Supply only	(MANUAL)	EA
CC1-31-5000	Screw Piles	1	-
31-5000	Screw Pile- 20x20" diameter	PS 1.Count	EA
CC1-07-3100	Shingles		-
07-3100	Shingles	(MANUAL)	SF
CC1-07-4633	Siding/Eaves/Downsputs	1	-
10-7000.01	Siding	SUM(Exterior1.Net Reference Side Surface Area ,Exterior2.Net Reference Side Surface Area,Exterior3.Net Reference Side Surface Area)	SF
10-7000.02	Post capping	CW 3.Count	EA
10-7000.03	Trim	sum(W1.Perimeter, W2.Perimeter, W3.Perimeter, W4.Perimeter)	LF
CC1-10-1410	Signage		LS
10-1410	Exterior signage	(MANUAL)	EA
CC1-01-1514	Site Security		-
28-0500	Site security	1	LS
CC1-80-5000	Storage Lockers		-
80-5000	Storage Lockers	Storage.Net Reference Side Surface Area	SF
CC1-05-1000	Structural Steel		-
05-5000.05	Seel beam	BS 1.Length	LF
05-5000.06	Steel column	CS 1.Count	EA
CC1-28-2300	Video Surveilance		-
28-2000	Video Surveilance	(MANUAL)	LS
CC1-07-1200	Waterproofing		-
07-1300	2-Plys of sopranele flam 180 waterproofing membrane to the exterior horizontal main deck	Retaining 1.Lenght	SF
CC1-12-2100	Window Treatments		-
08-5600.01	W1	(W1.Width* W1.Height)/ W1.Count	SF
08-5600.02	W2	(W2.Width* W2.Height)/ W2.Count	SF
08-5600.03	W3	(W3.Width* W3.Height)/ W3.Count	SF

08-5600.04	W4	(W4.Width* W4.Height)/ W4.Count	SF
CC1-08-5300	Windows Supply		-
08-5000.01	W1	(W1.Width* W1.Height)/ W1.Count	SF
08-5000.02	W2	(W2.Width* W2.Height)/ W2.Count	SF
08-5000.03	W3	(W3.Width* W3.Height)/ W3.Count	SF
08-5000.04	W4	(W4.Width* W4.Height)/ W4.Count	SF
FI	FINISHES		-
CC1-81-3100	Appliances		-
11-3000.01	Fridge	Refrigerator.Count	EA
11-3000.02	Diswasher	Dishwasher.Count	EA
11-3000.03	Oven	Oven.Count	EA
11-3000.04	Microwave	Microwave.Count	EA
34-0500	Delivery	Dishwasher.Count	EA
11-2300.01	Washer	Stacked Washer and Dryer.Count	EA
11-2300.02	Dryer	Stacked Washer and Dryer.Count	EA
11-2300.03	Laundry stacking	Stacked Washer and Dryer.Count	EA
11-2300.04	Stacking kit	Stacked Washer and Dryer.Count	EA
CC1-07-1900	Balcony Coating		-
09-6500.01	Balcony Coating- main floor	Balcony 1.Net Top Surface Area	SF
09-6500.02	Balcony Coating- remaining floors	Balcony 2.Net Top Surface Area	SF
CC1-07-1300	Balcony Membranes		-
07-1300.01	Balcony membranes	Balcony 1.Net Top Surface Area	SF
CC1-05-7300	Balcony Railings		-
05-7300	Balcony Railings	(MANUAL)	LF
CC1-89-0800	Building Security System		-
28-0500.01	2-GIG colour touchscreen control panel	DE1.Count	EA
28-0500.02	2-GIG wireless surface door contact	DE1.Count+ Door Single-Flush-DS1.Count+ Door Sliding-Closet-DL1.Count	EA
28-0500.03	2-GIG wireless surface window contact	SUM(W1.Count ,W2.Count ,W3.Count ,W4.Count)	EA
28-0500.04	2-GIG wireless motion	Door Single-Flush-DS2.Count	EA
28-0500.05	Standart finishing labour- local programming	Door Single-Flush-DS2.Count/2	HR
28-0500.06	Fire panel	1	EA
28-0500.07	Fixed english keypad	1	EA
28-0500.08	Security panel power supply transformer	1	EA
28-0500.09	12V Rechargable back up battery	1	EA
28-0500.10	RJ31 Security panel telco break out module	1	EA
28-0500.11	Standart finishing labour	1	HR
08-5000.04	W4	(W4.Width* W4.Height)/ W4.Count	SF
FI	FINISHES		-
CC1-81-3100	Appliances		-
11-3000.01	Fridge	Refrigerator.Count	EA
11-3000.02	Diswasher	Dishwasher.Count	EA

11-3000.03	Oven	Oven.Count	EA
11-3000.04	Microwave	Microwave.Count	EA
34-0500	Delivery	Dishwasher.Count	EA
11-2300.01	Washer	Stacked Washer and Dryer.Count	EA
11-2300.02	Dryer	Stacked Washer and Dryer.Count	EA
11-2300.03	Laundry stacking	Stacked Washer and Dryer.Count	EA
11-2300.04	Stacking kit	Stacked Washer and Dryer.Count	EA
CC1-07-1900	Balcony Coating		-
09-6500.01	Balcony Coating- main floor	Balcony 1.Net Top Surface Area	SF
09-6500.02	Balcony Coating- remaining floors	Balcony 2.Net Top Surface Area	SF
CC1-07-1300	Balcony Membranes		-
07-1300.01	Balcony membranes	Balcony 1.Net Top Surface Area	SF
CC1-05-7300	Balcony Railings		-
05-7300	Balcony Railings	(MANUAL)	LF
CC1-89-0800	Building Security System		-
28-0500.01	2-GIG colour touchscreen control panel	DE1.Count	EA
28-0500.02	2-GIG wireless surface door contact	DE1.Count+ Door Single-Flush-DS1.Count+ Door Sliding-Closet-DL1.Count	EA
28-0500.03	2-GIG wireless surface window contact	SUM(W1.Count ,W2.Count ,W3.Count ,W4.Count)	EA
28-0500.04	2-GIG wireless motion	Door Single-Flush-DS2.Count	EA
28-0500.05	Standart finishing labour- local programming	Door Single-Flush-DS2.Count/2	HR
28-0500.06	Fire panel	1	EA
28-0500.07	Fixed english keypad	1	EA
28-0500.08	Security panel power supply transformer	1	EA
28-0500.09	12V Rechargable back up battery	1	EA
28-0500.10	RJ31 Security panel telco break out module	1	EA
28-0500.11	Standart finishing labour	1	HR
CC1-76-2200	Cabinets		-
12-3500.01	Suite 1	Suite 1.Count	EA
12-3500.02	Suite 2	Suite 2.Count	EA
12-3500.03	Suite 3	Suite 3.Count	EA
12-3500.04	Suite 4	Suite 4.Count	EA
12-3500.05	Suite 5	Suite 5.Count	EA
12-3500.06	Suite 6	Suite 6.Count	EA
12-3500.07	Suite 7	Suite 7.Count	EA
12-3500.08	Suite 8	Suite 8.Count	EA
12-3500.09	Suite 9	Suite 9.Count	EA
12-3500.10	Suite 10	Suite 10.Count	EA
12-3500.11	Suite 11	Suite 11.Count	EA
12-3500.12	Suite 12	Suite 12.Count	EA
12-3500.13	Suite 13	Suite 13.Count	EA
CC1-82-3640	Granite Countertops		-

12-3600.01	Granite Countertops	Countertop Granite.Count	EA
CC1-82-3623	Laminate Countertops		-
12-3610.01	Suite 1	Suite 1.Count	EA
12-3610.02	Suite 2	Suite 2.Count	EA
12-3610.03	Suite 3	Suite 3.Count	EA
12-3610.04	Suite 4	Suite 4.Count	EA
12-3610.05	Suite 5	Suite 5.Count	EA
12-3610.06	Suite 6	Suite 6.Count	EA
12-3610.07	Suite 7	Suite 7.Count	EA
12-3610.08	Suite 8	Suite 8.Count	EA
12-3610.09	Suite 9	Suite 9.Count	EA
12-3610.10	Suite 10	Suite 10.Count	EA
12-3610.11	Suite 11	Suite 11.Count	EA
12-3610.12	Suite 12	Suite 12.Count	EA
12-3610.13	Suite 13	Suite 13.Count	EA
CC1-76-2010	Finish Carpentry Install		-
08-1000	Install door & frames	SUM(DL2.Count, DL1.Count, DL3.Count, DP1.Count, DS5.Count, DS4.Count, DS3.Count, DS2.Count ,DS1.Count, DB5.Count, DB1.Count ,DB4.Count, DB3.Count, DB2.Count,DE1.Count)	EA
10-1400	Install door numbers- suite entry doors	DE1.Count	-
06-4600.01	Install door trim	SUM(DL2.Perimeter, DL1.Perimeter, DL3.Perimeter, DP1.Perimeter, DS5.Perimeter, DS4.Perimeter, DS3.Perimeter, DS2.Perimeter,DS1.Perimeter, DB5.Perimeter, DB1.Perimeter,DB4.Perimeter, DB3.Perimeter, DB2.Perimeter)-SUM(DL2.Width, DL1.Width, Door DL3.Width, DP1.Width, DS5.Width, DS4.Width, DS3.Width, DS2.Width,DS1.Width,DB5.Width, DB1.Width,DB4.Width, DB3.Width, DB2.Width)	LF
06-4600.03	Baseboard	SUM(Utilities-Elevator.Length, Utilities.Length, Partition-Interior.Length, Mechanical-Interior.Length ,Interior2.Length*2 ,Interior1.Length*2 ,Exterior-Interior.Length ,Balcony-Interior.Length)	LF
10-2800.01	Bathroom acessories	Toilet.Count	EA
10-2800.02	Hardware	SUM(DL2.Count, DL1.Count, DL3.Count, DP1.Count, DS5.Count, DS4.Count, DS3.Count, DS2.Count ,DS1.Count, DB5.Count, DB1.Count ,DB4.Count, DB3.Count, DB2.Count,DE1.Count)	EA
10-2800.03	HMD doors	Door Single-Flush-HMD.Count	-
06-4600.02	Lobby trim	SUM(Corridor-Lobby.Lenght,Lobby-Elevator.Lenght, Lobby-Interior.Lenght, Lobby-Mailbox.Lenght, Lobby-Mechanical.Lenght, Lobby-Utilities.Lenght)	LF
08-8800.01	Vent boxes	Oven.Count	EA
08-8800.02	Covers	Stacked Washer and Dryer.Count	EA
CC1-06-2000	Finish Carpentry Materials		-
06-2001	Doors, jambs, casing, base, flat stock		EA
06-2001.01	3/O x 6/8 x 1 3/4" SC raw hardboard 20 min label door x 4 3/4"saw kerfed 20 min, label jamb c/w 2 UL spring hinges, 1BB hing, smoke seal	Door Single-Flush-DE1.Count	EA
06-2001.02	2/4 or 2/6 or 2x8 x 6/8 x 1 3/8"HC colonist x 4 1/2"primed pine jamb c/w 3 hinges	SUM(DS1.Count, DS2.Count, DS3.Count, DS4.Count, DS5.Count)	EA

06-2001.03	24" colonist bifold	(MANUAL)	EA
06-2001.04	36" colonist bifold	(MANUAL)	EA
06-2001.05	LF- aprox LM 295 MDF base/ casing	(MANUAL)	LF
06-2001.06	LF- aprox LM 395 MDF base (corridors)	Corridor.Length	LF
06-2001.07	Pieces 1 x 5 x 7' pine jamb	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002	Hardware		-
06-2002.01	UL rated magnum lever passage- 260	Door Single-Flush-DE1.Count	EA
06-2002.02	UL rated deadbolt locks KD, master and construction keyed	Door Single-Flush-DE1.Count	EA
06-2002.03	UL 180 degree door viewer	Door Single-Flush-DE1.Count	EA
06-2002.04	Magnum lever passage sets	SUM(DS2.Count,DS1.Count, DS4.Count, DS5.Count)	EA
06-2002.05	Magnum lever privacy sets	DS3.Count	EA
06-2002.06	Bifold knobs c/w back plate	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002.07	Spring stops	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002.08	H.D hinge pin stops	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)*3	EA
06-2003	Washroom accessories		
06-2003.01	Towel bars	Toilet.Count	-
06-2003.02	Toilet paper holder	Toilet.Count	-
CC1-76-2010	Finish Carpentry Install		-
08-1000	Install door & frames	SUM(DL2.Count, DL1.Count, DL3.Count, DP1.Count, DS5.Count, DS4.Count, DS3.Count, DS2.Count ,DS1.Count, DB5.Count, DB1.Count ,DB4.Count, DB3.Count, DB2.Count,DE1.Count)	EA
10-1400	Install door numbers- suite entry doors	DE1.Count	-
06-4600.01	Install door trim	SUM(DL2.Perimeter, DL1.Perimeter, DL3.Perimeter, DP1.Perimeter, DS5.Perimeter, DS4.Perimeter, DS3.Perimeter, DS2.Perimeter,DS1.Perimeter, DB5.Perimeter, DB1.Perimeter,DB4.Perimeter, DB3.Perimeter, DB2.Perimeter)-SUM(DL2.Width, DL1.Width, Door DL3.Width, DP1.Width, DS5.Width, DS4.Width, DS3.Width, DS2.Width,DS1.Width,DB5.Width, DB1.Width,DB4.Width, DB3.Width, DB2.Width)	LF
06-4600.03	Baseboard	SUM(Utilities-Elevator.Length, Utilities.Length, Partition-Interior.Length, Mechanical-Interior.Length ,Interior2.Length*2 ,Interior1.Length*2 ,Exterior-Interior.Length ,Balcony-Interior.Length)	LF
10-2800.01	Bathroom acessories	Toilet.Count	EA
10-2800.02	Hardware	SUM(DL2.Count, DL1.Count, DL3.Count, DP1.Count, DS5.Count, DS4.Count, DS3.Count, DS2.Count ,DS1.Count, DB5.Count, DB1.Count ,DB4.Count, DB3.Count, DB2.Count,DE1.Count)	EA
10-2800.03	HMD doors	Door Single-Flush-HMD.Count	-
06-4600.02	Lobby trim	SUM(Corridor-Lobby.Lenght,Lobby-Elevator.Lenght, Lobby-Interior.Lenght, Lobby-Mailbox.Lenght, Lobby-Mechanical.Lenght, Lobby-	LF

		Utilities.Lenght)	
08-8800.01	Vent boxes	Oven.Count	EA
08-8800.02	Covers	Stacked Washer and Dryer.Count	EA
CC1-06-2000	Finish Carpentry Materials		-
06-2001	Doors, jambs, casing, base, flat stock		EA
06-2001.01	3/O x 6/8 x 1 3/4" SC raw hardboard 20 min label door x 4 3/4"saw kerfed 20 min, label jamb c/w 2 UL spring hinges, 1BB hing, smoke seal	Door Single-Flush-DE1.Count	EA
06-2001.02	2/4 or 2/6 or 2x8 x 6/8 x 1 3/8"HC colonist x 4 1/2"primed pine jamb c/w 3 hinges	SUM(DS1.Count, DS2.Count, DS3.Count, DS4.Count, DS5.Count)	EA
06-2001.03	24" colonist bifold	(MANUAL)	EA
06-2001.04	36" colonist bifold	(MANUAL)	EA
06-2001.05	LF- aprox LM 295 MDF base/ casing	(MANUAL)	LF
06-2001.06	LF- aprox LM 395 MDF base (corridors)	Corridor.Length	LF
06-2001.07	Pieces 1 x 5 x 7' pine jamb	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002	Hardware		-
06-2002.01	UL rated magnum lever passage- 260	Door Single-Flush-DE1.Count	EA
06-2002.02	UL rated deadbolt locks KD, master and construction keyed	Door Single-Flush-DE1.Count	EA
06-2002.03	UL 180 degree door viewer	Door Single-Flush-DE1.Count	EA
06-2002.04	Magnum lever passage sets	SUM(DS2.Count,DS1.Count, DS4.Count, DS5.Count)	EA
06-2002.05	Magnum lever privacy sets	DS3.Count	EA
06-2002.06	Bifold knobs c/w back plate	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002.07	Spring stops	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)	EA
06-2002.08	H.D hinge pin stops	SUM(Door Single-Flush-DS1.Count, Door Single-Flush-DS2.Count, Door Single-Flush-DS3.Count, Door Single-Flush-DS4.Count, Door Single-Flush-DS5.Count)*3	EA
06-2003	Washroom accessories		
06-2003.01	Towel bars	Toilet.Count	-
06-2003.02	Toilet paper holder	Toilet.Count	-
CC1-79-6000	Flooring		-
09-6800.01	Carpet	Carpet 1.Net Top Surface Area	SF
09-3000.01	Tile	Tile 1.Net Top Surface Area	SF
09-3000.02	Bathtub tile	Bath tub.Count	EA
CC1-79-6400	Wood Flooring		-
79-6400	Hardwood	Laminate 1.Net Top Surface Area	SF
CC1-89-5100	Lighting Fixtures		-
26-5000.01	Lighting Fixtures 1	Light 1.Count	EA
26-5000.02	Lighting Fixtures 2	Light 2.Count	EA
26-5000.03	Lighting Fixtures 3	Light 3.Count	EA

26-5000.04	Lighting Fixtures 4	Light 4.Count	EA
26-5000.05	Lighting Fixtures 5	Light 5.Count	EA
26-5000.06	Lighting Fixtures 6	Light 6.Count	EA
26-5000.07	Lighting Fixtures 7	Light 7.Count	EA
26-5000.08	Lighting Fixtures 8	Light 8.Count	EA
CC1-80-5600	Shelving		-
10-5700.01	Wire	Shelve 1.Length	LF
CC1-10-2830	Vanity Mirrors		-
10-2830.01	Mirror 1	Toilet.Count	EA
10-2830.04	Banjo top	Toilet.Count	EA