2-3-2017 12:00 AM

BIM Assisted Design Process Automation for Pre-Engineered Buildings (PEB)

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A thesis submitted in partial fulfillment of the requirements for the Doctor of Philosophy degree in Civil and Environmental Engineering

Abstract

The effective adoption and implementation of Building Information Modeling (BIM) is still challenging for the construction industry. However, studies and reports show a significant increase in the rate of BIM implementation and adoption in mainstream construction activities over the last five years. In contrast, Pre-Engineered Building (PEB) construction, a specialized construction system which provides a very efficient approach for construction of primarily industrial buildings, has not seen the same uptake in BIM implementation and adoption. The thesis reviews the benefits and the main applications of BIM for the PEB industry as well as challenges of its practical implementation. To facilitate the implementation of BIM in the PEB industry, a BIM framework is adapted from Pre-fabrication (Pre-fab) industry and new workflows, process maps, and data-exchange strategies are developed. As the PEB industry traditionally makes significant use of automation in its design and fabrication process, accordingly this work investigates the technical challenges of incorporating automation into the proposed BIM process. Two new BIM concepts, “Planar Concept” and “Floating LOD”, are then developed and implemented as a solution to these challenges. To define the proper input/output criteria for automated BIM design processes, a numerical study was performed to identify an “Optimum LOD”.

A software implementation embodying the research outcomes was developed to illustrate the feasibility of the results. Its step-by-step deployment is analyzed and discussed using an example industry PEB design project. Further, the impact of this work is extended by integrating the developed BIM framework and automated design process with wind engineering design activities and tools and procurement systems. The study concludes that the deployment of the proposed BIM framework could significantly address existing issues in project design through to operation processes found in the PEB industry. Also, the results indicate the developed concepts have the potential for supporting the application of automation in the other sectors of the general construction industry. This thesis is written using the "Integrated Article" format and includes various complementary studies.

Keywords

Pre-Engineered Buildings (PEB), Metal buildings, Cold-formed steel system, Building Information Modeling (BIM), BIM implementation, BIM adoption, BIM framework, BIM interoperability, BIM Workflow, BIM Process, Planar Concept, Floating LOD, Level of Development (LOD), Level of Details, Level of Information (LOI), Optimum LOD concept, Return on investment (ROI) of BIM, Frequency and benefits of BIM uses, Application Based Classification Approach, Design Customization flaws, BIM design collaboration, BIM Engineering Integration, BIM integrated process for Wind Engineering, Material Quantification, MTO, BOM, 5D BIM, 5'D BIM modeling, BIM Coordinated Procurement System, BIM LOD, Purchase Requisition

Co-Authorship Statement

This thesis was completed under the supervision of Dr. John K. Dickinson and Dr. Girma T. Bitsuamlak. six articles were written and coauthored, the extent of the collaboration of the co-authors is stated below.

Chapter 2.

Paper title: Benefits, obstacles, and challenges in BIM implementation in Pre-Engineered Building (PEB) industry

Current Status Submitted to "ASCE - Journal of Construction Engineering and Management", January 2017.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

John K. Dickinson: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript.

Chapter 3.

Paper title: Building Information Modeling (BIM) framework for Pre-Engineered Building construction projects

Current Status Ready for submission.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

John K. Dickinson: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript.

Chapter 4.

Paper title: BIM Optimal Level of Development (LOD)

Current Status Ready for submission.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

John K. Dickinson: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript.

Chapter 5.

Paper title: Automation in Building Information Modeling (BIM) process; An example Pre-Engineered Building project

Current Status Ready for submission.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

John K. Dickinson: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript.

Chapter 6.

Paper title: Automated BIM-based Process for Wind Engineering Design Collaboration

Current Status Ready for submission.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

John K. Dickinson: Assisted in the editing and correction of the manuscript.

Chapter 7.

Paper title: Relative Concept for automation in BIM material quantification and 5’D BIM Coordinated Procurement System

Current Status Submitted to “ASCE - Journal of Computing in Civil Engineering”, February 2017.

Mohammad Delavar: Coordinated the study and contributed to the writing, editing, and correction of the manuscript.

John K. Dickinson: Assisted in the editing and correction of the manuscript. He is also the corresponding author of this article.

Girma T. Bitsuamlak: Assisted in the editing and correction of the manuscript.

Acknowledgments

Firstly, I would like to express my sincere gratitude to my advisor Dr. John K. Dickinson for the continuous support of my Ph.D. study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis. He was my hope when I was disappointed; he was my support when I had no one else to support me. I have never met a person of his graciousness and admirable personality. He has been my academic father. I have truly learned and benefited a lot from him. For this, I will eternally be grateful.

I would like to show my gratitude to my co-advisor Dr. Girma Bitsuamlak, for his support and substantial efforts on the guidance and arrangement of this research. He believed me and my work at its most critical time when I needed a supporter. It has always been a great honor to have him as my advisor.

I would like to thank Dr. Mocef Nehdi and Dr. Ashraf El Damatty for their support at the beginning of the research. This research could not be conducted without their initial influences and supports.

My Special thanks to Dr. Carl Haas and the University of Waterloo for their kind support and coordination provided for my research.

Also, I would like to thank Mr. Ashley Gibson as my industrial supervisor who respected the critical requirement of my real-life project base research and trusted me with my experimental approaches throughout the research and project designs. I would like to show my gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was developed.

I would like to express my deepest gratitude to Dr. Farhad Khamchin and Dr. Ahmad Aftabi at IAUM University for shaping my academic and research character and for preparing me for conducting a crucial Ph.D. research. They believed my potentials, and have supported me since I was a second-year undergraduate student.

I would like to thank the National Science and Engineering Research Canada (NSERC) for the kind funding through the Industrial Post Graduate Scholarship with sponsoring companies throughout the research.

My warmest thanks must be to my family. Thanks to my father, the true hero of my life, Mr. Ali Akbar Delavar who spent his entire life to make me what I am today. Many thanks to financial and technical support provided by himself and his engineering firm which made this research possible. Thanks to my mother Mrs. Marziyeh Etehadian Moghaddam, who never doubted, constantly supported and always loved. Even though we were thousands of miles away, they have been with me through every up, as well as every down. They mean the world to me, and I could not have become the person I am today without them both in my life.

Special thanks to my brothers Mr. Ali Delavar and Mr. Javad Delavar for taking care of all my troubles back home, so I could focus on my troubles in Canada. Your support, truly paved the way for me and it is greatly appreciated.

Many thanks to my parents in law, Mr. Karim Sarchami and Mrs. Fatemeh Shamloo for their support and love provided for my family and me in Canada.

Thanks to my beloved son, Mohammad Sadeq Delavar, the best son I could ever have, for his smiles encourage me to efficiently overcome the difficulties encounter in my life.

Last but not the least, thanks to my dear wife, Tahereh Sarchami. Her support, encouragement, quiet patience and unwavering love were undeniably the bedrock upon which the past ten years of my life have been built. Her tolerance of my occasional vulgar moods is a testament in itself of her unyielding devotion and love.

Dedication

To my parents, Ali Akbar Delavar and Marziyeh Etehadian Moghaddam for their endless love, support, and encouragement.

To my beloved wife, Tahereh Sarchami for patiently enduring and sharing these years of hard work.

To the hope of my life, my son, Mohammad Sadeq Delavar.

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Acronyms list

PEB	Pre-Engineered Building
BIM	Building Information Modeling
BIMs	Building Information Models
LOD	Level of Development
LOI	Level of Information
API	Application Program Interface
ROI	Return on Investment
DBB	Design-Bid Built
DB	Design Build
IPD	Integrated Project Delivery
SAP	Systems Applications and Products
AIA	American Institute of Architects
ISO	International Organization for Standardization
ISA	International Society of Automation
IFC	Industry Foundation Classes
CIS/2	CIMSteel Integration Standards/Version 2
ERP	Enterprise Resource Planning
nD	n Dimension Modeling

MTO	Material Take-off
QTO	Quantity Take-off
BOM	Bill of Material
PR	Purchase Requisition
PO	Purchase Order
AEC	Architecture, Engineering and Construction
MRP	Material Requirement Planning
NCR	Non-Conformance Report

Chapter 1

1.1 Background and Research Introduction

This thesis is written in an "Integrated Article" format. As such it is built from a combination of several papers and focused on how the use of Building Information Modelling (BIM) could be beneficially be applied to the PEB industry and how some benefits of the PEB approaches can be transferred back to the broader BIM enabled construction sector. This section introduces the topic coverage as presented in the thesis.

1.1.1 Pre-Engineered Building (PEB) and Building Information Modeling (BIM)

Pre-Engineered Building (PEB), otherwise known as metal building or cold-formed steel structural systems is one of the fastest growing steel structural systems, used dominantly for industrial buildings but increasingly for all types of buildings. Pre-engineered steel buildings can be optimized by avoiding using excess steel by tapering the beam sections as per the bending moment's requirements on the structural elements. This optimization in structural design reduces the steel consumption and the related project costs significantly. Also, as a common practice, the steel structure is prefabricated in advanced robotized shops and then transported to the site where it is rapidly erected (e.g. typical erection times are less than 6 to 8 weeks[1]). PEB has a number of advantages beyond reduced construction time and associated cost efficiencies such as flexibility of expansion, large clear spans, better quality control processes, low maintenance, compatibility with energy efficiency roof and wall systems, sustainability and single source responsibility. All these advantages have led to the PEB structural system to be used not only in industrial building applications but also in commercial, institutional, recreational, agricultural, aviation and military purpose buildings[1–3].

Building Information Modelling (BIM) involves the generation and management of digital representations of physical and functional characteristics of a construction project [4] to support effective collaboration and information reuse. Use of BIM has widely increased over the past decade by architects, engineers and construction practitioners [5]. However, despite the increase in the usage of PEB construction [6], BIM has not made the same inroads into the PEB industry as in other segments of the construction sector. Reviewing the major PEB players' design and fabrication process development in North America suggests that the PEB industry generally does not employ BIM [7–9].

BIM adoption in the PEB industry, similar to other industries, would require a change in the existing practices to utilize BIM over part or throughout the entire PEB project lifecycle [10]. This study reviews the PEB design, fabrication and erection processes to identify essential processes throughout the PEB industry project life-cycle and consider the potential impact of adopting and applying BIM in the PEB industry. Factors considered include the industry's need to remain competitive and effective; anticipated obstacles for successful BIM implementation in PEB; the possible risks, legal and contractual issues; and the technical requirements for BIM implementation in the PEB. After reviewing these factors, this Ph.D. study proposes that BIM would be of benefit to the PEB industry if approached with an appropriated developed comprehensive BIM framework. Finally, a case study is presented to show the merits of BIM application for the PEB industry.

As an emerging research field, BIM has limited existing studies; therefore, the review of available literature goes beyond academic publications to include practical manuals, handbooks, white papers and technical reports of BIM-related applications (i.e. [4,5,8,9,11]). Articles in well-respected online newsletters (i.e. buildingSMART Canada, National Institute of Building Sciences/buildingSMART alliance) that reflect the latest developments of BIM were also consulted. These studies have done much to explore the status of BIM adoption as well as its usage, costs, and benefits.

1.1.2 BIM Level of Development (LOD)

Although there is a high level of growth in BIM implementation in the construction industry, interoperability and BIM Level of Development (LOD) challenges still remain. Identifying an appropriate level of model development to meet specific project requirements and then developing BIM models to that level have been identified as essential challenges to overcome[12].

LOD research questions, in general, can be categorized into two: “how much a BIM model is required to be developed for specific uses in a project?” and “how to develop a model to that level efficiently?”. In this thesis (i) a brief review of most commonly utilized LOD specifications are presented and then compared; (ii) a mathematical approach for finding a hypothetical optimal LOD to be considered for generalized application cases is discussed; and (iii) a flexible approach for design is presented where the model development is nearly automated and the model LOD is kept adjustable.

1.1.3 Automation in BIM Processes

The recent results of internationally trusted BIM surveys indicate a significant increase in BIM awareness and motivation for BIM adoption by the general built asset industry[13,14]. However, a BIM model needs to be developed to at least a certain Level of Development (LOD) to be useful in supporting many analysis, procurement and construction activities (Reference: Chapter 3 of [12] and [12,15,16]). However, manual development of a BIM model to an advanced LOD can be costly and a time-consuming process. Hence, the “efficiency” of the current BIM procedures, particularly the model development process, is regarded to be a primary concern regarding successful deployment of BIM in the PEB industry and further adoption in the construction sector at large.

For the PEB context being investigated in this thesis, design and analysis automation already forms a critical component of its processes. New automation concepts and implementations are introduced and developed to match these industry requirements.

1.1.4 BIM integration for Engineering Processes

As mentioned earlier, the PEB industry makes use of integrated engineering analysis during its design process to minimize costs while meeting project requirements. This study focuses on BIM-based engineering design/analysis process integration in which an intelligent modeling software integrates design and analysis methods with the BIM model to produce design specifications. Development of this information integration will form the base for what will be passed on to the owners and operators for use in the building's systems to be used for example in energy analysis, structural analysis, and emergency evacuation planning, etc.

The implementation issues associated with integrating engineering analysis and design into a BIM-based system for the PEB industry are investigated for the case of computational fluid dynamics analysis. To illustrate a possible solution to these issues, support for integrated Wind Engineering analysis was incorporated into the PEB design system by using an automatically created 3D model of the building and computational domain and sharing data through a central database.

1.1.5 BIM automated material quantification; BIM coordinated procurement system

The utility of an automatically developed design is not limited to the engineering domain. It can also be highly relevant to the business activities of a company, in particular, the entire materials procurement and work-order development activities that support the eventual construction of a facility. BIM models are typically developed to LODs that support early design cost estimation, but require significant expert effort to refine to more accurate quotes. Further research shows that material take-off (MTO or in other references Quantity Take-offs QTO) and the resulting bill of materials (BOM) from reliable automatically developed designs provide a good starting point for more accurate cost calculations. Furthermore, intelligent mechanisms can be integrated into the tool to allow for further refinement of these estimates to take into account aspects of the design that are not explicitly modelled.

Again, the BIM-based design system is extended to illustrate and evaluate the potential of this approach for the PEB sector for the example PEB project.

1.2 Objectives of the study

The overall objective of this research was to develop an automated BIM-based (BIM-assisted) system for design to operation process of PEB construction projects. It is expected that the use of such a BIM system could significantly increase the efficiency the design and construction process of a building, and during its operational lifecycle as well. Such a proposed system could increase the quality of the construction projects outcome while improving the cost and time efficiency of the design to operation processes. The PEB industry was targeted as the case study from the construction industry due to its unique and digital design and construction approach. PEB projects are typically digital throughout pre-design scenarios, pre-fabrication, automated and robotized fabrication, integrated structural design, integrated mechanical design, full early stage cost estimation and complete automated material quantification system. The main challenge to reach the objective through case study industry was lack of a proper development and implementation of BIM technology for the PEB industry. Therefore, reaching the general objective of this research was not possible without an expanded study, examination and development of BIM technologies for practical implementation in PEB industry.

1.2.1 Specific objectives

The following are specific sub-objectives or milestones of this study.

1. To review and to introduce the benefits and advantages of BIM implementation for PEB industries as well as challenges and risks involving it and propose some resolutions for the challenges.
2. To develop a comprehensive BIM framework for PEB industry for practical implementation and examine the feasibility and practicality of the proposed BIM framework through implementation and application to a real-world case study.
3. To develop automated BIM model development processes for the PEB industry example to match existing PEB industry norms.
4. To identify the Level of Development (LOD), the BIM models need to be developed to by the automated design process to meet the PEB industry requirements.
5. To examine the feasibility and practicality of the developed automation in BIM processes for supporting integrated engineering design. In particular, to examine the process of integrating Wind Engineering simulation and analysis processes with the developed automated BIM system as an example.
6. To assess the feasibility and practicality of the developed automation in BIM processes for supporting an automated BIM coordinated procurement system and a material quantification system.

1.3 Organization of the Thesis

This thesis has been prepared using the "Integrated-Article" format. This chapter, Chapter 1, introduces the overall scope and structure of the thesis. This is followed by presenting the general and specific objectives of the current study. These objectives are addressed in detail in the following six chapters.

Chapter 2: Benefits, obstacles, and challenges in BIM implementation in Pre-Engineered Building (PEB) industry

This chapter discusses the benefits, risks, and challenges involved in implementing BIM in the PEB industry. The potential benefits and the most important challenges are examined by using a case study project. Given the existing inflexible/non-BIM design process for PEB systems, this chapter argues that a significant amount of change orders and reworks costs could be eliminated in collaborative PEB projects (involving multiple construction disciplines) by defining a BIM workflow for the design and construction phases. In conclusion, this chapter suggests a need for the development of a comprehensive BIM framework; which could be developed for PEB industry based on the similar existing BIM framework and processes used in the Pre-Fabricated building industry.

Chapter 3: Building Information Modeling (BIM) framework for Pre-Engineered Building construction project

Reviewing the traditional design to operation process of PEB industry, this chapter explains some of the main challenges of PEB industry in dealing with the complex and collaborative project. As an effort to facilitate the implementation of BIM in PEB industry, a BIM framework adopted from Pre-fabrication (Pre-fab) industry is introduced. The Proposed BIM framework uses the similarities between pre-fab industry and PEB for the development of a framework. This framework suggests a scope separation for designing PEB building component and conventional structure. Then it automates the PEB design processes. The necessary workflows and process maps, data-exchange strategies are developed so that the PEB BIM framework is implementable. In particular, some standard extensions and two new BIM concepts, "Planar Concept" and "Floating LOD", are proposed to overcome some technical challenges in the development of the PEB BIM frameworks. The developed software BIM tool implementation was based on all the provided technical background and illustrated processes as BIM framework for PEB, is introduced in this chapter. This API software was developed to study the feasibility and deployment of the proposed framework. The API interface and its step by step deployment procedure based on the framework are illustrated, analyzed and discussed. The deployment of the proposed BIM framework for PEB could significantly address typical issues in design to operation process of the projects in PEB industry.

Chapter 4: BIM Optimal Level of Development (LOD)

The goal of this work in this chapter is to identify what the optimum or ideal LOD should be based on common industry project applications of BIM and their associated costs and benefits. The proposed LOD optimum is found using a mathematical approach based on industry assessments of the advantages and Return on Investment (ROI) data collected in recent respected international BIM surveys for different BIM uses. A Pre-Engineered Building (PEB) project example is used to show that LOD300 models can realize with reasonable effort and those models can support the desired uses, like coordination, estimation, and clash detection.

Chapter 5: Automation in Building Information Modeling (BIM) process; An example Pre-Engineered Building project

This chapter reviews a number of BIM applications that automate the project design to operation processes. A Planar Concept approach that allows for the automation of BIM model development processes is proposed in order to increase the detail of the model. This is expected to allow the extra use of model information without excessive modeling costs. The difficulties in developing such automation for BIM without limiting the BIM capabilities and customizing the general BIM design and construction industries are discussed. The ability to relate/link model elements to larger systems and switch between representations as well as the ability to generate both a design and analytical models in parallel are important in automation of engineering design. Finally, to evaluate the feasibility of the developed concepts and algorithms for automating the BIM model development, an API BIM-based software was developed by authors. The success in implementation of the API software was examined through developing a BIM model for an example PEB.

Chapter 6: Automated BIM-based Process for Wind Engineering Design Collaboration

In this chapter, the development of an automated BIM system to facilitate an integrated BIM system for structural design and Wind Engineering analysis is presented. The BIM integrated system collaborates with primarily computational aerodynamics assessment tools (but also useful for experimental approaches) during building design phase, using a central database and outputs 3D model of the building and the computational domain. The results suggest a successful integration which could significantly improve the building design quality and facilitate the engineering design collaboration. It is also observed that the results could be applied to the general AEC industry.

Chapter 7: Relative Concept for automation in BIM material quantification, 5'D BIM Coordinated Procurement system; An example PEB project

By providing a comprehensive background discussion on the standard process of material quantification and construction project procurement, this chapter discusses some of the technical and non-technical challenges in the implementation of 5D BIM modeling. Some of these challenges can be classified as challenges of an adequate 3D BIM model development -Level of Development (LOD) issues- for an effective BIM-based material take-off, difficulties associated with the process of such model development and absence of a comprehensive process definition for all cost estimation operation. Based on the discussion provided, some resolutions such as "relative material take-off" concept is proposed, and its process is illustrated in this chapter. Also, some of the developed concepts such as optimum LOD, floating LOD for addressing the LOD related issues and for creating automation in model development processes for BIM cost estimation and management system is evaluated in this chapter. A comprehensive BIM coordinated procurement system is introduced as 5'D BIM modeling system in this chapter. Its processes and workflows are extensively explained through evaluation by a developed BIM-based API and stand-alone software. Some of the advantages of this advanced BIM system such as visualization and improved decision-making ability are discussed through its application for BIM 5D and 5'D modeling of an example PEB project.

Chapter 8: Conclusion

Chapter 8 presents a summary and the conclusions of the entire thesis together with recommendations for further research work.

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Chapter 2

2 Benefits, obstacles, and challenges in BIM implementation in Pre-Engineered Building (PEB) industry

Abstract

The adoption and implementation of Building Information Modeling (BIM) is still challenging for both the public and the private construction sectors. Nevertheless, studies and reports show a significant increase in the rate of BIM implementation and adoption in mainstream construction activities over the last five years as general tools and practices mature. In contrast, Pre-Engineered Building (PEB) construction, a specialized construction system, has not seen the same uptake in BIM implementation and adoption. The PEB system provides a very efficient approach for construction primarily industrial buildings, and it is due to this advantage that it has seen increased use over the last decade. This paper discusses the benefits, risks, and challenges involved in implementing BIM in the PEB industry. The potential benefits and the most important challenges are examined by using a case study project. Given the existing inflexible/non-BIM design process for PEB systems, this paper argues that a significant amount of change orders and reworks costs could be eliminated in collaborative PEB projects (involving multiple construction disciplines) by defining a BIM workflow for the design and construction phases. In conclusion, this paper suggests a need for the development of a comprehensive BIM framework; which could be developed for PEB industry based on the similar existing BIM framework and processes used in the Pre-Fabricated building industry.

Keywords: Pre-Engineered Buildings (PEB), Metal buildings, Cold-formed steel system, Building Information Modeling (BIM), BIM implementation, BIM adoption, BIM framework, BIM interoperability, BIM Workflow

2.1 Introduction

Pre-Engineered Building (PEB), otherwise known as metal building or cold-formed steel structural system is one of the fastest growing steel structural systems, used dominantly for industrial buildings but increasingly for all types of buildings. Pre-engineered steel buildings can be optimized by avoiding using excess steel by tapering the beam sections as per the bending moment's requirements on the structural elements. This optimization in structural design reduces the steel consumption and the related project costs significantly. Also, as a common practice, the steel structure is prefabricated in advanced robotized shops and then transported to the site where it is rapidly erected (e.g. typical erection times are less than 6 to 8 weeks[1]). PEB has a number of advantages beyond reduced construction time and associated cost efficiencies such as flexibility of expansion, large clear spans, better quality control processes, low maintenance, compatibility with energy efficiency roof and wall systems, sustainability and single source responsibility. All these advantages have led to the PEB structural system to be used not only in industrial building applications but also in commercial, institutional, recreational, agricultural, aviation and military purpose buildings [1–3].

Building Information Modeling (BIM) involves the generation and management of digital representations of physical and functional characteristics of a construction project [4]. Use of BIM has widely increased over the past decade by architects, engineers and construction practitioners [5]. Despite the increase in the usage of PEB construction [6], the authors have observed that BIM has not made the same inroads into the PEB industry as in other segments of the construction sector. Reviewing major PEB players design and fabrication process development in North America suggests that the PEB industry generally does not employ BIM [7–9].

BIM adoption in the PEB industry, similar to other industries, would require a change in the existing practices to utilize BIM over part or throughout the entire project lifecycle [10]. This paper reviews the PEB design, fabrication and erection processes to identify essential processes throughout the PEB industry project life-cycle and consider the potential impact of adopting and applying BIM in the PEB industry. Factors considered include the industry's need to remain competitive and effective; anticipated obstacles for successful BIM implementation in PEB; the possible risks, legal and contractual issues; and the technical requirements for BIM implementation in the PEB. After reviewing these factors, this paper proposes that BIM would be of benefit to the PEB industry if approached with an appropriated developed comprehensive BIM framework. Finally, a case study is presented to show the merits of BIM application for the PEB industry.

Being an emerging research field, BIM has limited existing studies; the literature review, therefore, goes beyond academic publications to include practical manuals, handbooks, white papers and technical reports of BIM-related applications (i.e.[4,5,8,9,11]) and articles in well-respected online newsletters (i.e. buildingSMART Canada, National Institute of Building Sciences/buildingSMART alliance) that reflect the latest developments of BIM. These studies have explored the status of BIM adoption as well as its usage, costs, and benefits.

2.2 BIM state-of-the-art in the construction industry vs. PEB industry

2.2.1 BIM adoption and maturity levels

According to Digicon/IBC National BIM Survey [7], most Canadian construction industry stakeholders believe that adopting BIM has directly improved visualization and document coordination, and notably, these rewards rated much higher than profitability. Most believe that clients will increasingly insist on the use of BIM (although the survey could not indicate whether deliverables should be required in some form of BIM format). A 71% majority said that contractors would require delivery of BIM design files although this will not carry much weight in a Design-Bid-Build procurement process in which the contractor takes whatever is offered, due to lack of authority over the designers[9]. According to the 2015 NBS National BIM Report, BIM awareness and adoption have been increased to 50% of all AEC organizations in the UK, and it is estimated that it will reach to 95% within only five years [8].

Clearly, even as BIM continues to develop, not all businesses will adopt systems and technologies at the same rate. BIM adopters will need to go through a managed process of change, involving both their internal organizational interfaces and external supply-base and clients. A maturity model is shown in Fig. 2-1, with levels from 0 through 3 [12], was developed by the UK Department of Business Innovations and Skills (BIS). A majority of the market is still working with Level 1 processes, and the best in class are experiencing significant benefits at Level 2. [13].

2.2.2 BIM Level of Development (LOD)

The core of the MPS is the level of detail (or development with the acronym of LOD) definitions (Table 2-1) which describes the steps of the BIM element logical progress. The levels of details range from the lowest level (100) of conceptual approximation to the highest level of representational precision (500) as defined in Table 2-1.

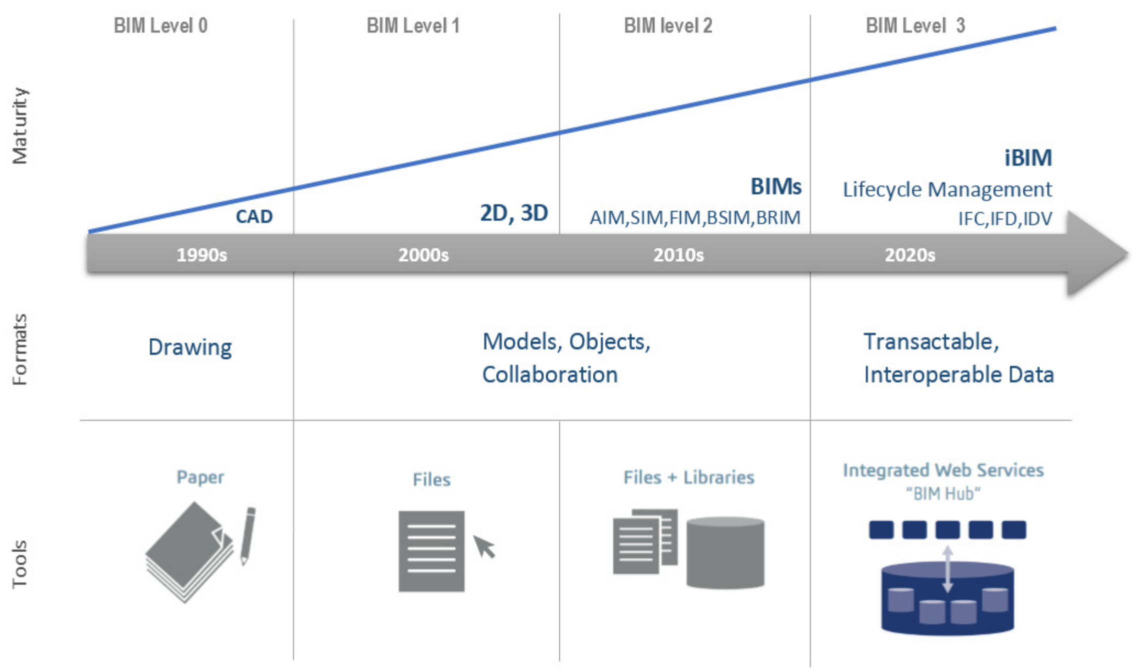

Fig. 2-1 BIM Maturity levels U.K. Adopted from BIS [14]

Table 2-1 Model Progression specifications (AIA).[a] [13]

Level of detail Model content	100	200	300	400	500
	Conceptual	**Approximate geometry**	**Precise geometry**	**Fabrication**	**As-built**
Design & Coordination **(function/from/behavior)**	Non-geometric data or line work, areas, volumes, zones etc.	Generic elements shown in three dimensions • Maximum size • Purpose	Specific elements Confirmed 3D Object geometry • dimension • capacities • connections	Shop drawing/fabrication • purchase • manufacture • Install • specified	As-built • actual

[a] A portion of table adapted from American Institute of Architects, AIA-E202 element model table.

As the paper focusses on the steel PEB (metal building industry), it is prudent to describe another important LOD specification introduced by the BIM Forum [15]. The 2015 updated specification, uniquely suggests a LOD specification for metal buildings (Table 2-2) under section B1010.10, Floor Structural Frame (Cold-Formed Metal Framing) [16]. This specification focuses mostly on the existence of the element components and attributes in the building model, rather than describing the development and condition of the model as AIA describes [13]. This paper suggests that PEB industry is lacking BIM adoption and implementation, which would place it in the late BIM Level 1 stage. Reports such as IBC survey[7] further confirm that the PEB industry is behind other industries regarding BIM development.

Table 2-2 BIM Forum Level of Development (LOD) Specification for Cold-Formed Metal Framing [16]

Level of Development				
100	**200**	**300**	**350**	**400**
Assumptions for structural framing are included in other modeled elements such as an architectural floor element that contains a layer of assumed structural framing depth; or, schematic structural elements that are not distinguishable by type or material. **Assembly depth/thickness or component size and locations still flexible**	Element modeling to include: • Rough architectural masses • Approximate member depth • The desired member spacing	Element modeling to include: • floor element with design-specified locations and geometries Required non-graphic information associated with model elements includes: • Member size, depth, and material with sloping geometry • Spacing and end elevations • Design loads • Deflection criteria	Element modeling to include: • Members modeled at any interface with wall edges (top, bottom, sides) or opening through wall • Bridging or straps	Element modeling to include: • Welds • Connections • Member fabrication part number • Any part required for complete installation

The BIM Forum is known for offering the visual LOD classification (describing LOD by illustrating all the BIM model elements for different building components) [16]. However, for PEB industry (Cold-Formed Metal Framing), it only verbally describes the classification. This fact suggests the lack of well-developed BIM LOD classification for PEB industry while other AEC industries have fairly developed LOD classification by different BIM institutes.

2.2.3 Interoperability issues

One of the main issues in BIM implementation in any types of industries is the interoperability [17]. To address the interoperability problems for other construction domains, for example, the AEC industry has developed some data exchange standards such as Industry Foundation Classes (IFC), CIMsteel Integration Standards Release 2 (CIS/2) [18], and Construction to Operations Building information exchange (COBie) [19]. All three have seen significant industry application. The development of such standards makes possible the realization of long-held visions of Computer Integrated Construction (CIC) supported by integrated data models and information management.

The Industry Foundation Classes (IFC) is perhaps the largest and most ambitious effort that is being undertaken to develop an integrated building model [20] with the hope of achieving the goal of CIC. Its ongoing development is supported by buildingSMART International (bSI) and several of its components have achieved ISO standards status. CIMsteel Integration Standards, the result of the Eureka EU120 CIMsteel Project, is a set of formal processing specs that allows computer software suppliers to make their structural steel engineering programs compatible. The CIS standards are based upon a formal product model known as Logical Product Model (LPM) which defines a logical framework for data regarding entities, attributes, and relationships among these types of entities [21]. The COBie standard has been recently developed (at 2007) by National Institute of Building Sciences (NIBS) [19,22] and it is more focused on non-geometrical information transfer is a structured two-way spreadsheet style communication package. [23,24]. By far, IFC protocol is known to be the most support standard by software suppliers regarding BIM data exchange, and it has experienced an evolutionary journey from 1995 on its very first generation [17] to IFC4 on 2015 [25]. On the other hand, CIS/2 is known for its well development to address steel structural modeling, design and analysis data exchange [18]. The prime focus of the current study will be on discussing the relevance of the CIS/2 protocol to the design to erection process for PEB industry.

2.3 Benefits of BIM in PEB

2.3.1 Importance of BIM for PEB

There are a number of different drivers for BIM adoption in the broader construction industry. Some of the BIM drivers can push BIM adoption directly such as government or client requirements, and some others are more indirect such as competitive market positioning. For some firms, maintaining or improving project quality, safety and productivity would be strong drivers. Managerial drivers for BIM adoption might include improved communication with operatives, cost savings, and monitoring, condense delivery schedules, accurate construction sequencing, clash detection, and (semi-automated) schedule generation. BIM can influence the construction phase of a project by facilitating increased use of pre-fabrication. In operational phases, information in BIM models can facilitate facilities management activities with substantial savings over the life-cycle of a facility for the owners [26]. Not all of these drivers may be applied particularly to PEB construction industry. PEB is already known to be very efficient in regards to time and the cost of fabrication and installation [3]. However, there are some BIM benefits relevant to the PEB industry as will be discussed.

The construction industry is highly competitive, and the current and reported signs of multiple economic downturns have amplified this [8]. The PEB industry is not different in being exposed to the same situation. Especially in the harsh economic situation, the industry requires more efficient and economical construction systems such as PEB. Thus, it makes sense for PEB industry stakeholders to seek to improve their efficiency even more. As it was indicated earlier, the rate of BIM implementation by PEB firms is currently very low. Furthermore, the other parts of the construction sector provide examples of how to use BIM successfully to improve their productivity [5,7–9]. Hence, the risk for “early adopters" as innovators in PEB industry should be lower than experienced by other in the early years of BIM, and the potential performance and efficiency benefits should be greater. The key is to identify and support the correct BIM drivers for the PEB industry.

Some BIM drivers such as reducing costs or facilitating facilities management activities can affect the business development approach and available markets in industry directly. As was mentioned earlier, single source responsibility has been counted as one of the main advantages of the current PEB system in marketing and business development. However, as will be discussed, this feature can be two-sided and may cause a real barrier for BIM adoption in PEB. Considering the advantageous side of this fact, BIM can be a key factor in increasing the lifecycle quality of the delivered product. The most advanced BIM products currently available have the capability to deliver environmental, energy, cost, schedule and spatial analysis; and as such, can be used collaboratively by project stakeholders to deliver real whole life value (WLV) to clients [27]. After the completion of the project during operations, the client (building owner) and/or the operator will need the facility as-built model for the greatest life-cycle benefits. The BIM model can be linked to an existing facility management system to provide an accurate and complementary data set; that makes asset management faster and more accurate [28]. BIM can provide a data-rich, platform by which to program and monitor preventative maintenance and carry out space management activities. Preventive maintenance scheduling enables facility managers to proactively organize maintenance activities, appropriately allocate maintenance staff, and lower corrective maintenance and emergency maintenance repairs. Given that the information about building element maintenance is logged into the model correctly pre-handover, facilities managers can anticipate saving up to 70% on what would have otherwise been reactive maintenance [29].

PEB buildings are not always used as simple as storage areas. Nowadays PEB systems are used to build different types of complex building projects such as power plant enclosures, gas and other energy resource stations enclosures, some advanced military enclosures and some large size merchants showrooms, which have complex architectural features. Thus, it is reasonable to take advantage of BIM capabilities to assist in improving the design and documentation as repeatedly reported for other building systems and industry applications [5,7,8]. Also, BIM models can offer walk-through visualizations to assist clients in the decision-making process and, therefore, reduce later change orders [11]. Contributions from geographically distributed designers can be integrated with confidence and can be demonstrated to the client visually [30]. Some example of PEB projects with more complex architectural features are shown in Fig. 2-2. BIM can improve the project design process for these types of PEB projects as they include complex design in correlation with architectural components and features. Thus, BIM adoption by PEB industry seems very applicable for streamlining design activities and improving design quality.

Fig. 2-2 Complex PEB buildings with architectural features [31,32]

BIM offers contractors an alternative means of communication with their workforce. Due to the significant increase in the globalization of the construction workforce, the numbers of non-native speaking operatives have increased, thus increasing the importance of supplementing translators or interpreters with visual models [33]. BIM provides a visual 3D Model that can be explored by site construction crews as an easy communication and project clarification tool. Furthermore, this communication can be a two-way process. There may be constructability issues that have simple, site-level solutions for which craftsmen or operatives may have suggestions. In this, BIM, through visual animation, can promote collaboration on a micro-level with the workforce [26]. Also, 4D BIM extends the use of the 3D models to support enhanced planning and monitoring of the job site safety [34].

During design, BIM can produce visual representations and animated simulations of physical clashes between different elements of the building and based on model detail, between the building and temporary works [35]. Traditionally, clashes between building components often remain undetected until the construction stage of the project which would result in redesign and rework and often incurred non-recoupable costs [27,30]. Clash detection can offer savings of up to 10% of contract value and reduce project duration by up to 7% [30]. These savings go some way towards the target of 15% project savings through BIM set by the UK Government (as one the major BIM drivers) [36], therefore reducing the common causes of disputes prevalent within the construction industry.

Thus, as mentioned, BIM can have a substantial influence on construction communication and clash detection as part of "project coordination" activities. However, historically, the PEB industry has generally been applied to projects with less complexity in design or erection process. Fig. 2-3 shows some examples of a simple application of non-complex PEB system for storage buildings.

Fig. 2-3 Non-complex PEB buildings [37,38]

However, PEB is regularly applied to more complex building applications such as power plant enclosures, gas stations enclosures and some advanced military enclosures. In such applications, the PEB steel structure as one component is interactively involved in the project design in conjunction with other disciplines such as mechanical and electrical. It is observed that due to lack of BIM implementation in PEB, 3D BIM model integration with other project components is not accessible or easily possible. Some examples of PEB projects in energy generation and transportation industry are shown in Fig. 2-4. These projects are very complicated geometry wise. Also, these projects involve many different structural, mechanical, and electrical systems that require collaborative design and installation in the context of each other and the PEB structure (illustrated in Fig. 2-4).

Fig. 2-4 Complex PEB Projects in energy generation industry (left inside a complex project, photo taken by author, right Outside a complex PEB project[39])

In these scenarios most installed components will most likely have good quality BIM models available, but due to the lack BIM implementation and deployment for the PEB system, data exchange and project coordination (particularly clash detection and 3D coordination) is not easily possible for these types of projects. As an example, a costly resolution for clashes between PEB structure and a pipe, detected at the project construction phase (in the absence of BIM pre-clash detection at the design phase) is shown in the Fig. 2-5, as it was observed in one of the research case study projects.

Fig. 2-5 Clashes detected at the construction phase of a PEB project in the absence of BIM implementation.

Hence, improved communication and coordination is perhaps the most significant driver of BIM adoption for the PEB industry.

2.3.2 Case study project to evaluate the importance/demand of BIM for PEB industry

During the study, different projects were carefully monitored to assess the applicability of BIM to the PEB industry and to identify the relative importance of different BIM applications. In one of the energy industrial PEB projects, two small PEB buildings (diffusers enclosures in the size of 38'-6" x 30'-11" by the eave height of 30') were studied and surveyed to identify which factors are more influential in the absence of a BIM process.

The results of the survey were obtained from the site reports and Non-Conformance Reports (NCR), from August 12th, 2013 to October 8th, 2013, during the erection phase of the buildings.

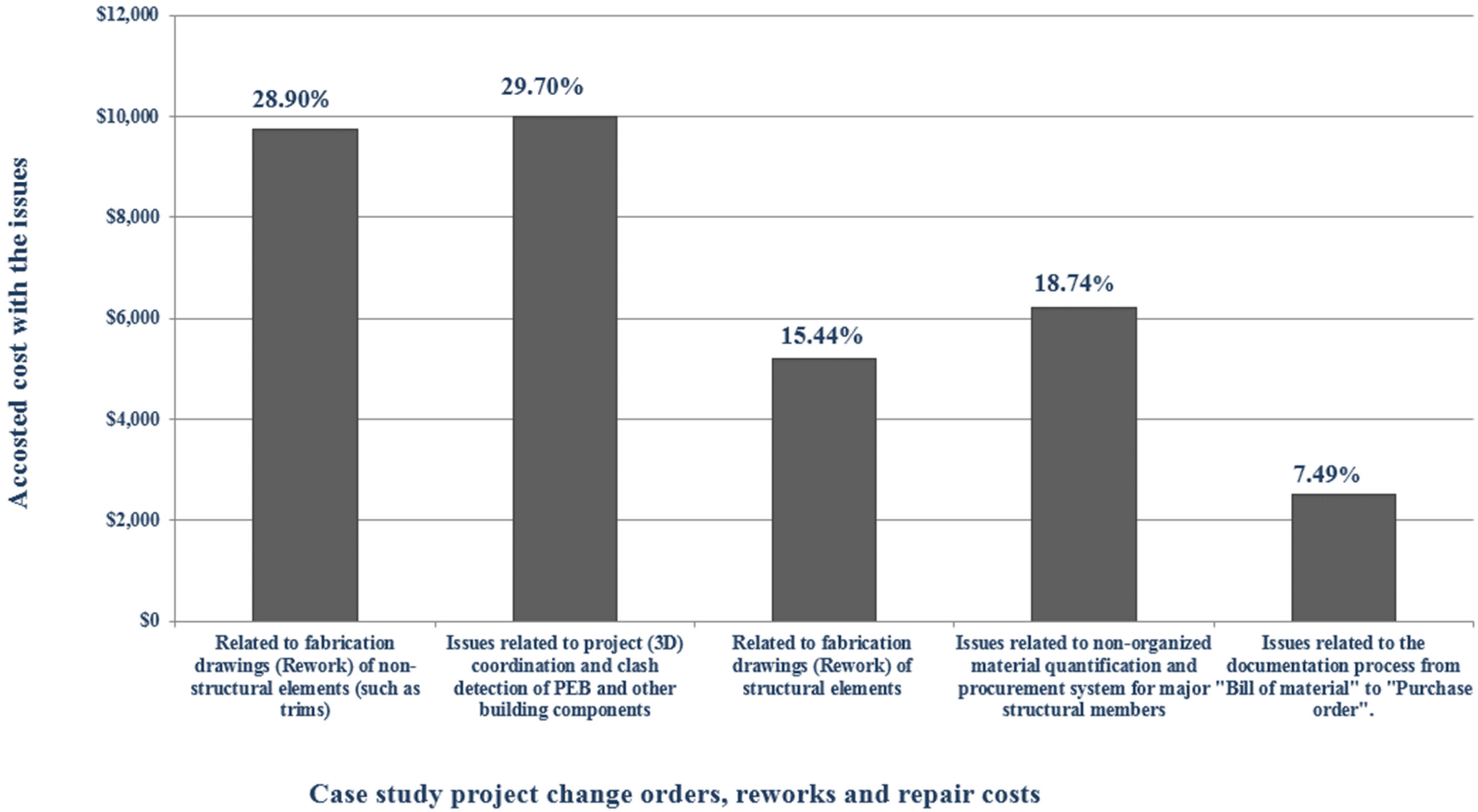

Fig. 2-6 A graph illustrating the project change orders, rework and repair costs based on the case study.

For a PEB case study, Fig. 2-6 shows that significant extra costs were incurred due to project coordination issues during design and construction (first two bars) and during subsequent procurement (last three bars). The fundamental support from BIM for 3D clash detection, design workflow, and data exchanges ability of BIM has the potential to significantly help this project with coordination and collaboration activities between disciplines. In addition, the use of BIM could also address some of the inconsistencies between the required Bill of Material (BOM) and the Purchase Order (PO) avoiding or reducing reorders as during the procurement process.

2.4 Obstacles and challenges implementing BIM in the PEB industry

It has been said that "It is important to keep in mind that BIM is not just a technology change, but also a process change" [11]. From this, we can take that there are some technical challenges in developing and adopting BIM into the PEB industry as well as non-technical challenges. The technical challenges are mostly around interoperability issues, and a lack of BIM enabled PEB design tools. (Unfortunately, there is also a lack of drivers for PEB design tool authors to incorporate BIM.) The non-technical issues include establishing new processes and changing old habits, the existing business development methods for PEB industry, lack of PEB industry awareness of BIM and potential risks and liabilities in adopting BIM in PEB industries.

2.4.1 Business development method for PEB industry

2.4.1.1 General PEB industry approach for market development

As was mentioned earlier, the PEB market generally considers it advantageous to have "single source responsibility" [2,3,6]. At least, theoretically, all building components are compatible, and all the probable matters are already considered. The building owner or the construction manager does not have to keep track of a number of suppliers. Busy small building owners especially understand the ease of dealing with one entity if anything fails during occupancy. "This convenience is a major selling point of the systems" [2]. The current state of the PEB sector is that major market players have dominated it. These players are mostly multinational fabricators with several giant service centers consisting of fabrication and manufactory plants, design and management offices around the globe. This market structure creates two types of problems.

For the most case, each PEB manufacturer has, at least, some proprietary products, which distinguish its building components from the other manufacturers. These components have been developed and optimized over a decade or more for performance and fabrication. In contrast, BIM tends to start with standardized and generalized building systems, as a tool to solve global scale interoperability issues. This unique PEB domain inhibits application of generic solutions.

In any types of construction, contracts or partnership such as ‘Design-Bid-Build’ (DBB), which the design and construction services are contracted with several parties, project coordination (during the design and construction phases) becomes challenging in regards to handling the RFIs and change orders. These challenges occurred due to missing (or indirect) communication between project stakeholders. This problem becomes more critical in projects, which fabrication and early erection processes start with short lag with the start of the design process by different parties. In that case, handling the early or late change orders sometimes becomes costly. Marketing and business development plans share a similar structure and flow for most of the PEB industry. Some intermediate companies are used to act as a dealer to sell the buildings for PEB manufacturers while the manufacturers themselves try to focus on the structural design and fabrication scheduling and management [2,40,41]. The overall process is shown in the Fig. 2-7.

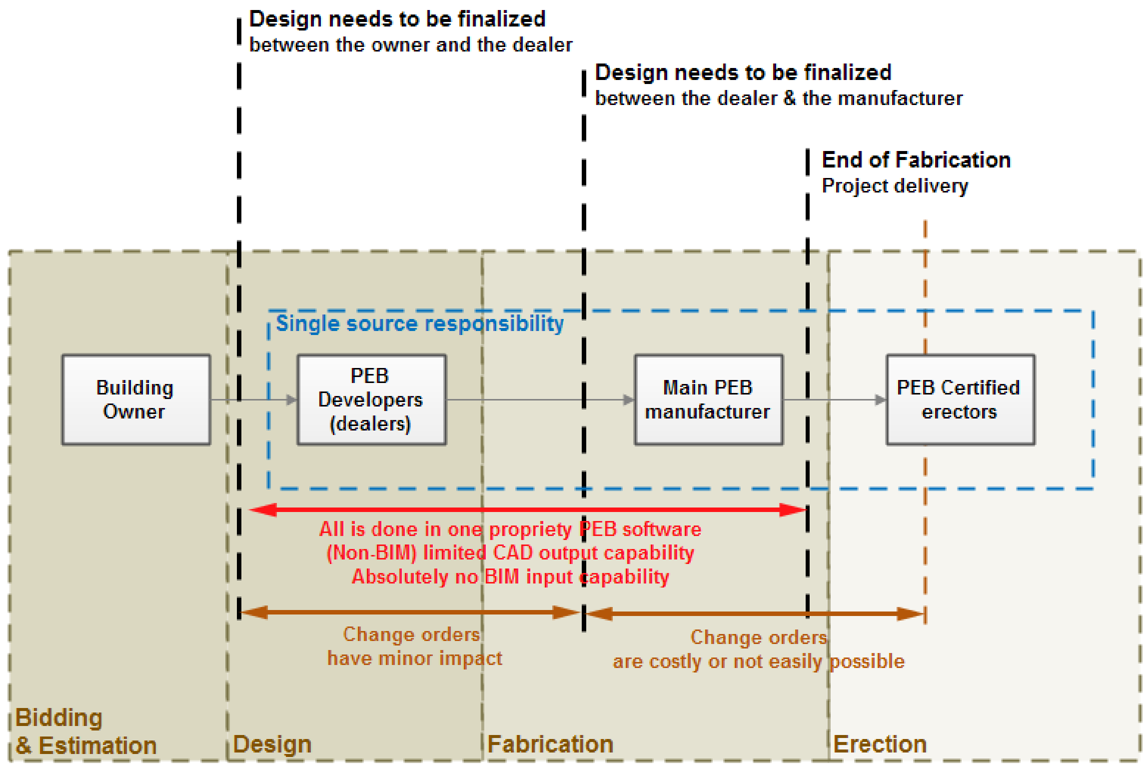

Fig. 2-7 Design to erection process of PEB buildings in regards to the project partnership only in structural discipline

As it is shown in Fig. 2-7, this process not support the application of BIM in any phase of a project, as one non-BIM propriety software is responsible for all the tasks from the initial planning and layout definition to the structural analysis, design, documentation and finally the shop drawings (fabrication drawings). Most of these software work similarly process-wise; such by pushing one button all the processes are completed. It is clear that if a change in PEB design is required due to change in a design by other project stakeholders (non-PEB stakeholders such as mechanical design), then whole the PEB building needs to be redesign and rerun again. In contrast, BIM design process is far more flexible with regards to changes in design during the project life-cycle. The authors feel that the traditional inflexible PEB process probably causes a number of problems that could be alleviated by adopting a collaborative workflow with other disciplines (see Fig. 2-8).

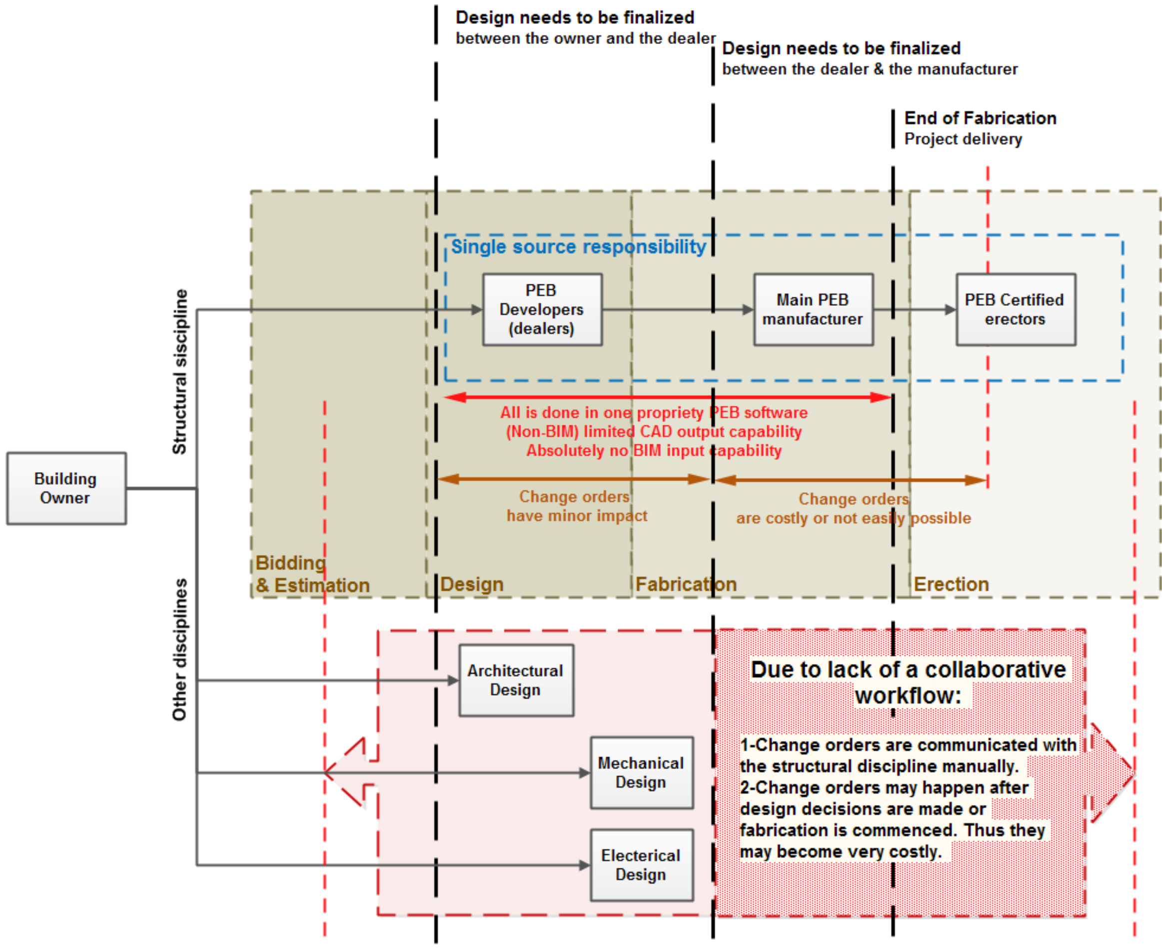

Fig. 2-8 Design to erection process of PEB buildings in regards to the project partnership in all different disciplines

2.4.1.2 Varco Pruden Building (VP) processes for design and marketing as PEB case study

VP has developed a proprietary PEB design system over the last half a century [42]. As one of the pioneers in the PEB industry VP started developing an automated design to fabrication system, in the early 90s, which was later upgraded to a Computer Aided Design (CAD) system called "VPCommand." As a software system, it includes functionality for developing the purchase orders, handling the early estimation, a tool for the final structural design in service centers and the creation of documentation and fabrication information (Fig. 2-9).

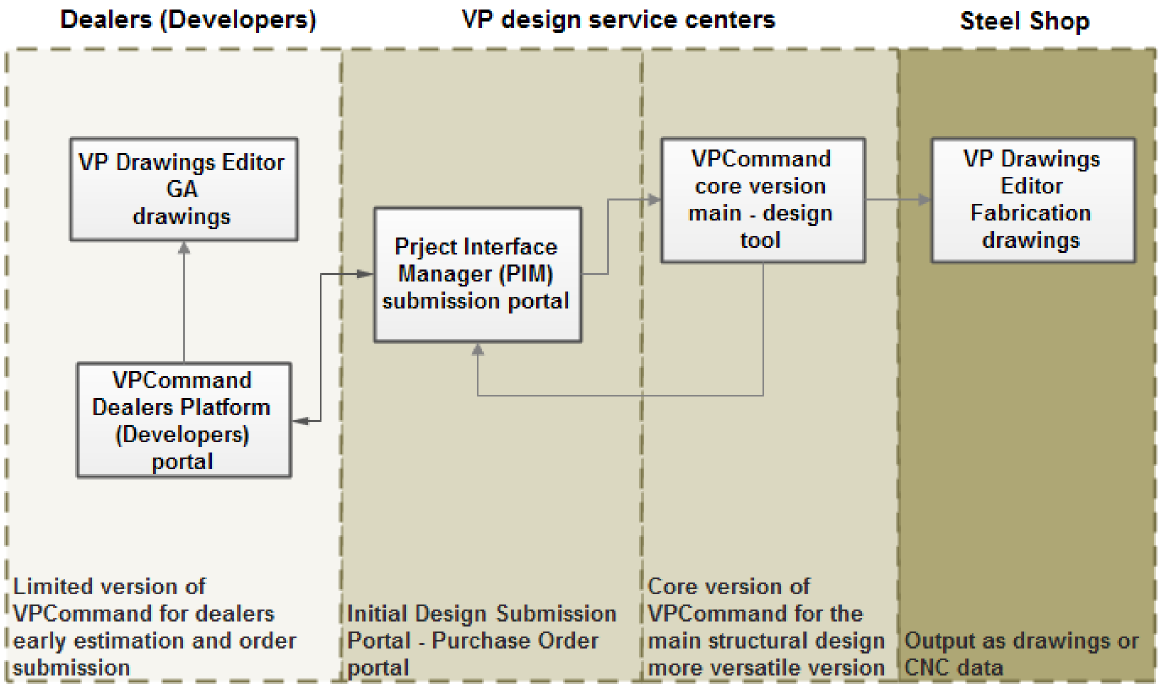

Fig. 2-9 VP design system using VPCommand

For three years VP CAD system and its PEB design software were observed and examined in order to develop a BIM process for the PEB industry and potentially a matching design process for BIM software. It is worth mentioning that VPCommand is a very powerful CAD tool and inspirational for developing a BIM tool which could address its collaboration and coordination shortcomings.

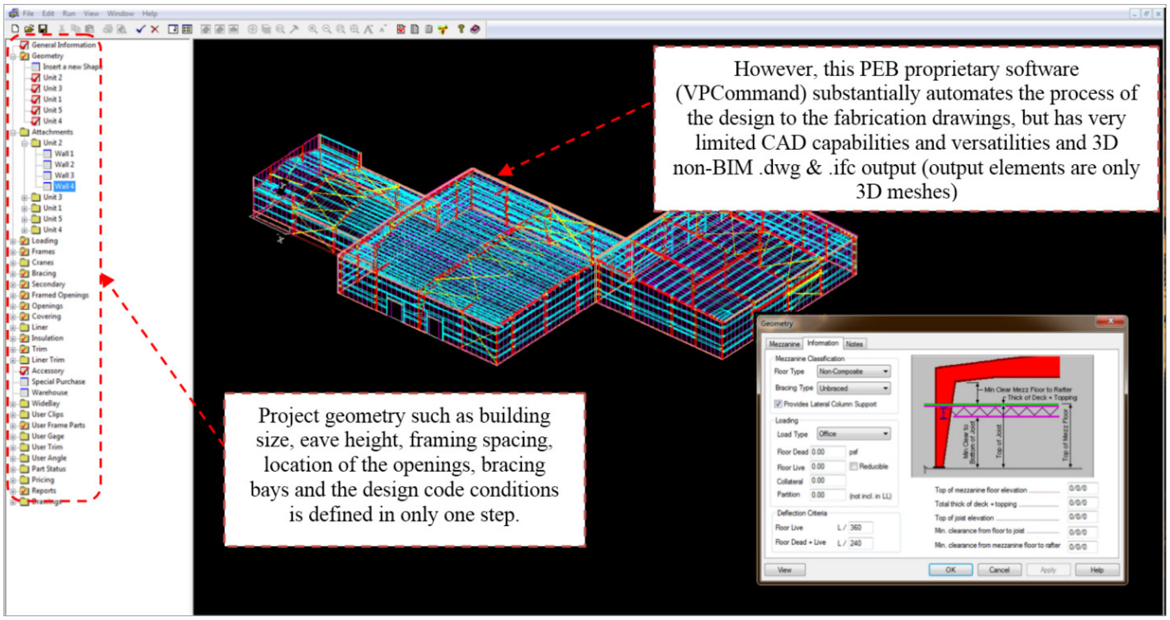

Fig. 2-10 VPCommand software interface

2.4.2 Interoperability issues

BIM interoperability also remains as an obstacle in the way of BIM implementation for PEB industry. Currently, none of the open data exchange protocols, such as IFC, CIS/2, or COBIE are supported by PEB propriety software for the exchange of design data between different disciplines (illustrated in Fig. 2-8). Thus, the ability to import and export BIM models for project and life cycle uses (a fundamental activity in BIM workflows) is not available to the PEB industry.

2.4.3 Lack of motivation for PEB design tool authors to incorporate BIM

Historically PEB industry has developed their proprietary software [41] for the estimating, designing and fabricating the PEB buildings. As over the time, they have optimized their shop and fabrication process in conjunction with the design software capabilities, it has become the most economical practice to go with the single source responsibility approach [2]. Most software vendors, which offer software solutions for the different phases of a project from estimating to construction, have lost their motivation to develop BIM software for PEB industry. Clearly, a BIM software, which designs and creates the shop drawings for PEB building components, will not have significant market value, if it is not ever used by the major PEB fabricators. Because of this, the PEB industry has not drawn much attention from major construction sector software vendors. However, drivers such as new expectations for project coordination of PEB with other disciplines are beginning to create a recognizable demand and market value for a BIM-based PEB software platform.

2.4.4 Lack of PEB industry awareness of BIM

As it is shown in the Fig. 2-7, PEB dealers are mostly responsible for the design phase of the PEB projects. Over time, the dealers have developed a non-BIM process for design development and coordination. Based on the understanding achieved from the case study and observing the PEB industry during the study period, major PEB manufacturers and fabricators, which have a financial and technical influence on PEB software development, have not been exposed to the difficulties and challenges of the project design and coordination as much as the dealers have. In the broader construction industry, BIM may be broadly accepted as the best replacement for traditional design systems, but in the PEB sector, the major players have too much invested in their proprietary systems to consider replacing them. One observation from the case study project mentioned in section 3.2, VP as the PEB building supplier was not directly exposed to or accountable for any of the issues that lead to project change orders, rework and repair costs. All of the responsibilities for the project development, as it was explained in 4.1.1, belongs to the PEB dealers and project developers. Hence, as it was indicated in the last chapter (4.3), PEB developers (dealers) are the ones demanding BIM implementations for the PEB industry to assist in dealing with the project design development and design coordination.

2.4.5 Potential risks and liabilities adopting BIM

Using BIM in a project may raise important contractual issues associated with project responsibilities and risks, contractual indemnities, copyright, and use of documents that are not addressed through the standard industrial contract forms. These issues, potentially, are major concerns on for adoption of BIM in industries [17].

2.4.5.1 Risk allocation

The PEB industry, like other major construction industries, is exposed to some general risk issues concerning BIM implementation, particularly in regards to data exchange and BIM model transfer.

BIM risks in all industries can be divided into two broad categories: legal (or contractual) and technical. The first risk is the insufficient determination of ownership of the BIM data and the need to protect it through copyright laws and other legal channels. To prevent a disagreement over copyright issues, the best solution is to stipulate in the contract documents ownership rights and responsibilities. When project team members other than the owner and architect/engineer contribute data into the building information model, licensing issues can arise. For example, equipment and material vendors offer designs related to their products for the ease of the lead designer in hopes of inducing the designer to specify the vendor’s equipment. While this practice might be good for business, licensing issues can arise if the designs were not produced by a designer licensed in the location of the project [30].

Another contractual issue to address is who will control the entry of data into the model and be responsible for any inaccuracies. Taking responsibility for updating BIM data and ensuring its accuracy entails a lot of risks. Requests for complicated indemnities by BIM users and the offer of limited warranties and disclaimers of liability by designers are necessary negotiation points that need to be resolved before BIM technology is used. It also requires more time spent inputting and reviewing BIM data, which is a new cost in the design and project administration process. Although these new costs may be dramatically offset by efficiency and schedule gains, they are still a cost that someone on the project team will incur. Thus, before BIM technology can be fully adopted, not only must the risks of its use be identified and allocated, but the cost of its implementation must be paid for as well. The integrated concept of BIM blurs the lines of responsibility so much that risk and liability are likely to be enhanced [27] until new standards of practice are established.

2.4.5.2 Intellectual property rights

In comparison to two-dimensional CAD drawings and specifications, BIM Models contain a tremendous amount of information which can be transmitted quickly, efficiently, and can be easily extracted and reused in whole or in part [17]. In particular, the final BIM Model may have a significant value for fabricators. In PEB industry, the final goal is to supply the engineered building, where the greatest portion of the net profit of the project is located for the fabricators and manufacturers. Sharing high LOD BIM models of the PEB building components including the steel structure with the other project stakeholders (e.g. case dealers and owners) will always bring up some related intellectual property issues. High-level LOD 3D models can be used for extraction of critical data such as shop and fabrication drawings or allow for reverse engineering of designs. Subsequently, the net profit of the PEB manufacturer could be at risk. Thus, the PEB industry is traditionally not interested in sharing any 2D or 3D data with higher levels of accuracy and development.

2.5 BIM use in prefab industry as template for PEB industry

2.5.1 Value of the research on PEB industry case

It is noted that the application of BIM for PEB industry makes this research distinguished from other BIM-based research on the conventional construction industry (non-PEB). The main reason for such difference can be found in the nature of design and fabrication process in this industry. Construction industries such as PEB (metal buildings) and Pre-fab use an advanced design process which addresses most of their specialized construction tasks during the design phase of a project. The methodology in such industries is to precisely address all the design related matters as well as required predictions and consideration for the fabrication, material supply, and installation/construction phase. In addition, PEB itself has a very automated design process progressing from the schematic to comprehensive fabrication drawings which will be discussed in this section. The PEB industry, which has all these attributes, thus makes it a unique case study for BIM implementation. Studying the application of BIM in this demanding domain will establish processes and expectations for how BIM can support automated design processes and integrated supply chains, trends that are emerging, and thus relevant, in general non-PEB industries.

2.5.2 Prefab vs. PEB distinguishing factors

There is some confusion in the industry regarding the difference between Pre-Engineered Buildings (PEB) and conventional Pre-Fabricated Buildings (Prefab). Both are often called pre-fabricated due to their fabrication off-site and installation process at the project site. However, there is a huge difference between these two industries due to the different applications, definitions, and approaches. The difference between these two systems can be categorized into two main topics:

2.5.2.1 Building components and shapes and primary frames optimization

The distinguishing factor of PEB system is how the structural members are optimized by tapering them based on bending moment in contrast to Prefab building structures which have conventional defined structural elements for columns, beams, and bracing elements. PEB components mainly consist of 3-Plate elements, which are cut, and machine welded offsite. Prefab elements can consist of all sort of standard profiles manufactured based on the countries national standards such as AISC or CISC shape profiles [1].

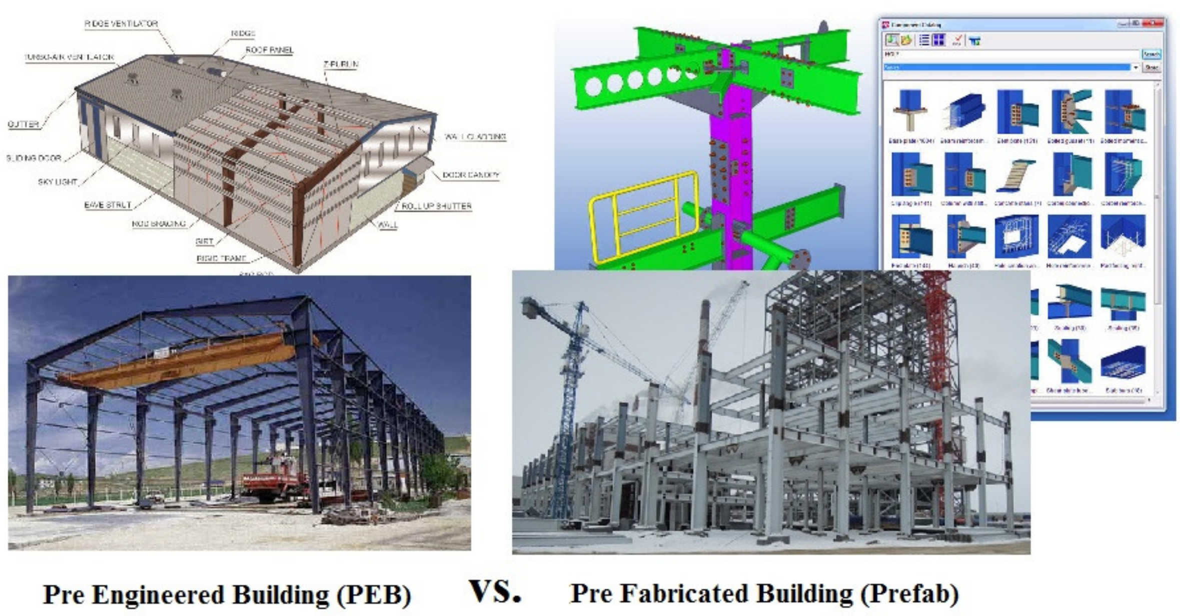

Fig. 2-11 Pre-Engineered Building vs. Pre-Fabricated Building (Prefab) [43–46]

2.5.2.2 Design and analysis approach

The PEB industry is more focused on long span single story applications, and they have developed their propriety software to automate the process of design and structural optimization for these structures [41]. However, in the Prefab industry, similar to all other types of the conventional building industry, the process of the design and documentation is done using different software tools, and extra tasks need to be done to complete the process as it is illustrated in the Fig. 2-12. Thus, the process of the design for a conventional prefab building is more time consuming but more flexible for incorporating changes and customizing the geometrical development of the project. In addition, the Prefab process is more collaborative as different disciplines can contribute to the overall design process.

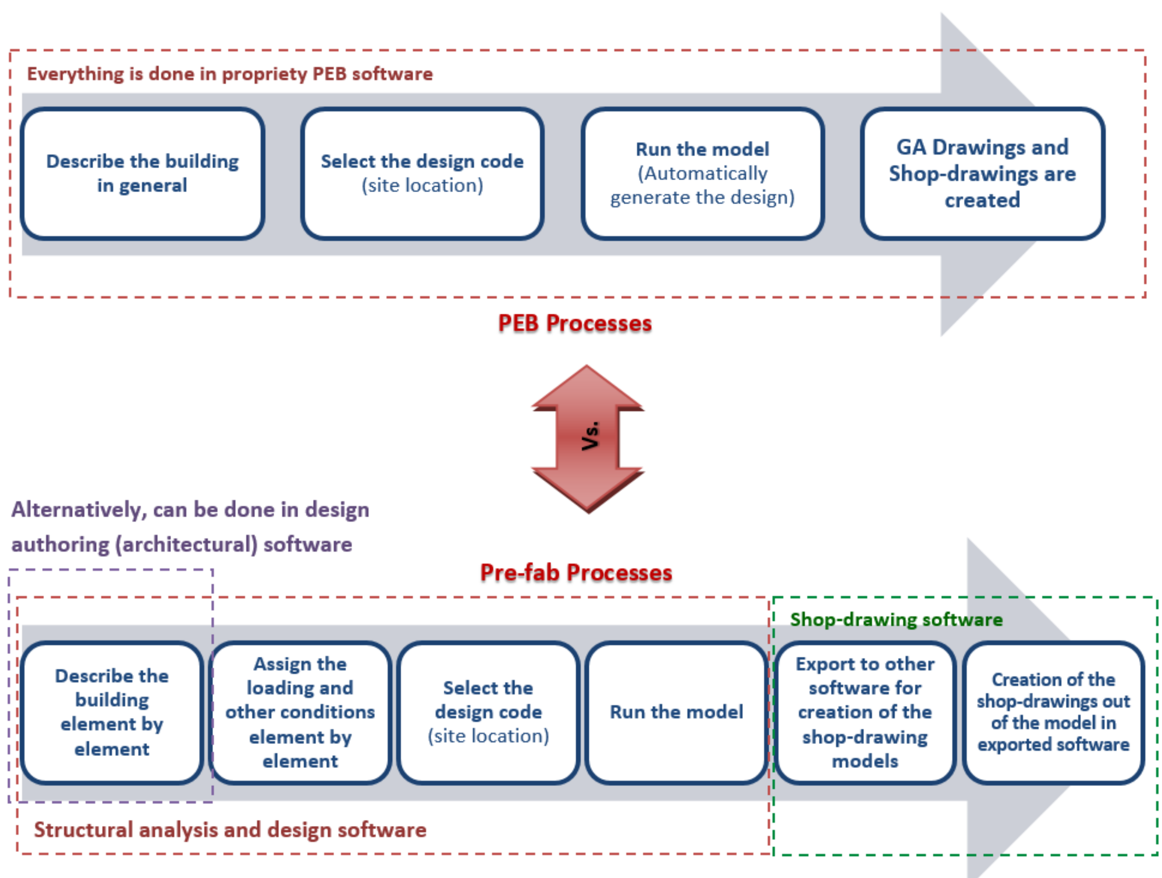

Fig. 2-12 Difference between PEB and Prefab building design process

The Prefab design and fabrication is not dependent on any dominant market players, as is the case for PEB, and the process of the design is more flexible. In addition, the Prefab industry uses standard manufactured steel profiles, which can be easily sourced. All these features have made BIM well-suited to the sector and have led to higher levels of BIM adoption in prefab industry over the past decade [9]. It is observed that due to the similarities in the nature of the both systems (regarding the prefabrication processes), some attempts have been made by several major BIM software vendors such as Autodesk and Bentley, to design PEB buildings using the Prefab process [46,47] although their approaches missed the automation usually inherent in the PEB design process.

2.5.2.3 Using BIM framework for Prefab as template for the PEB BIM framework development

As it was explained in the last section, there is an absence of a well-defined and flexible collaboration (work-flow and data-exchange) between different project stakeholders in the traditional PEB industry. The authors feel that this lack is a significant contributor the PEB industry’s challenge with project coordination. In contrast, the Prefab industry uses a general BIM process defined for BIM implementation, illustrated in Fig. 2-13. This process is defined to include the different project stakeholders over the design and construction phases of the project. In addition, a clear protocol for BIM data exchange between parties involved is also defined. Therefore a BIM model, which is developed through a collaborative process, can be used to support the various tasks in the different phases of a project [48].

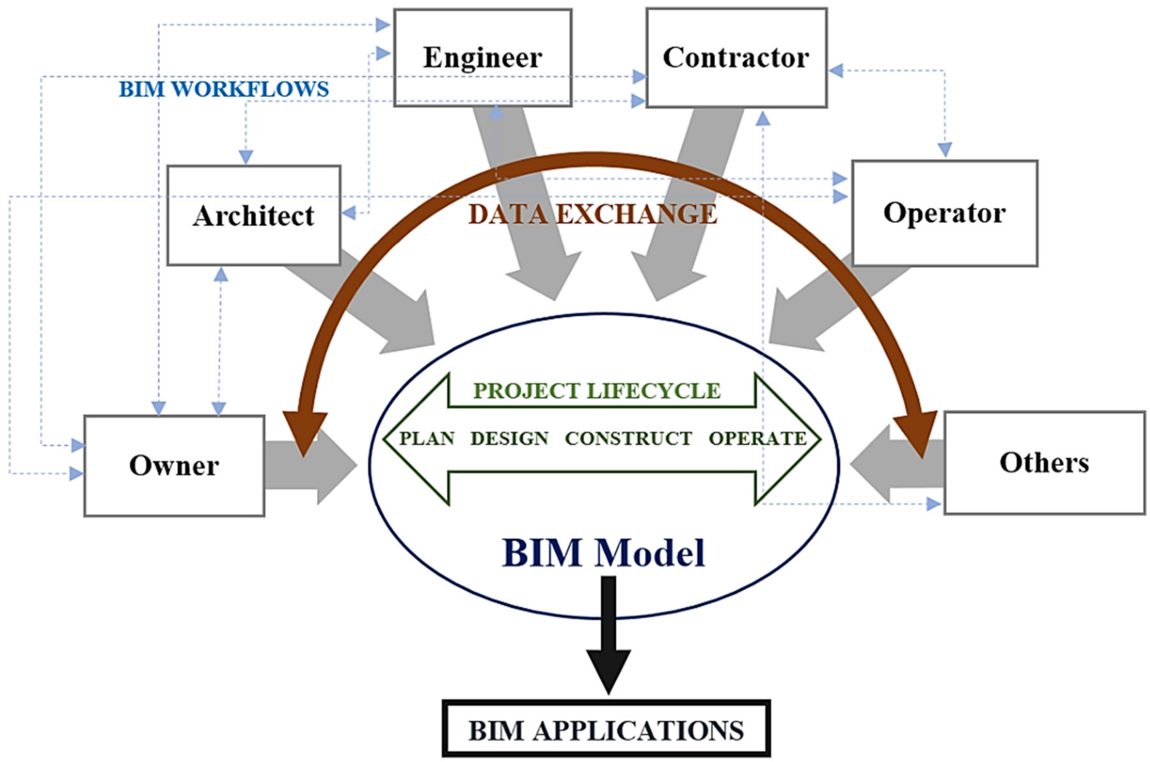

Fig. 2-13 BIM Process for general industry

However, fully utilizing and applying this BIM process and approach for (the Prefab BIM framework) to the PEB sector, in its current state [46,47], is not recommended due to two main reasons:

a. The business market and nature for PEB is still manufacturer centered. A PEB supplier/manufacturer is still the 'single responsible source' and adopting a collaborative process such as shown in Fig. 2-13 is not efficient enough for the PEB industry.

b. As it was illustrated in Fig. 2-12, many different parties are involved in the process of design using prefab BIM workflow. This fact enhances the collaborative and flexible nature of the process, at the cost of potentially introducing data-exchange (interoperability) issues. Also, a collaborative process is relatively too time-consuming for a typical PEB design process time frame as shown in Fig. 2-8

2.5.2.4 A brief review of the suggested BIM framework for PEB adopted from Prefab

As it was explained, fully utilizing the Prefab BIM framework for the PEB sector would result in a system that was less efficient than the current PEB system. It is reminded that one of the most important advantages of the PEB over other structural system is its automated, single source and time-saver (efficient) process. To maintain the advantage of automation in a BIM process for PEB, an adapted prefab BIM process is required. Thus, the current traditional CAD system which has been developed by PEB industry would need to remain in use although a transition from 2D modeling to 3D modeling would be required. Using this approach all the PEB structural (including primary tapered frames, secondary cold-formed girts and purlins, all the connections, etc.) as well as none-structural elements (including metal siding sheets/panels, insulations, barriers, etc.) could still be automatically designed using the PEB process and tools as illustrated in Fig. 2-12 (user only describes the general broad building characteristics). To deal with other conventional/non-PEB building components (such as mezzanines, structural supports for equipment, etc.) should be separately processed using the standard prefab BIM design process illustrated in Fig. 2-12 (where a very detailed input is required). This dual process approach is illustrated in Fig. 2-14. The resulting designs from each process would reside in multiple models but could be integrated into a final BIM model using BIM interoperability features.

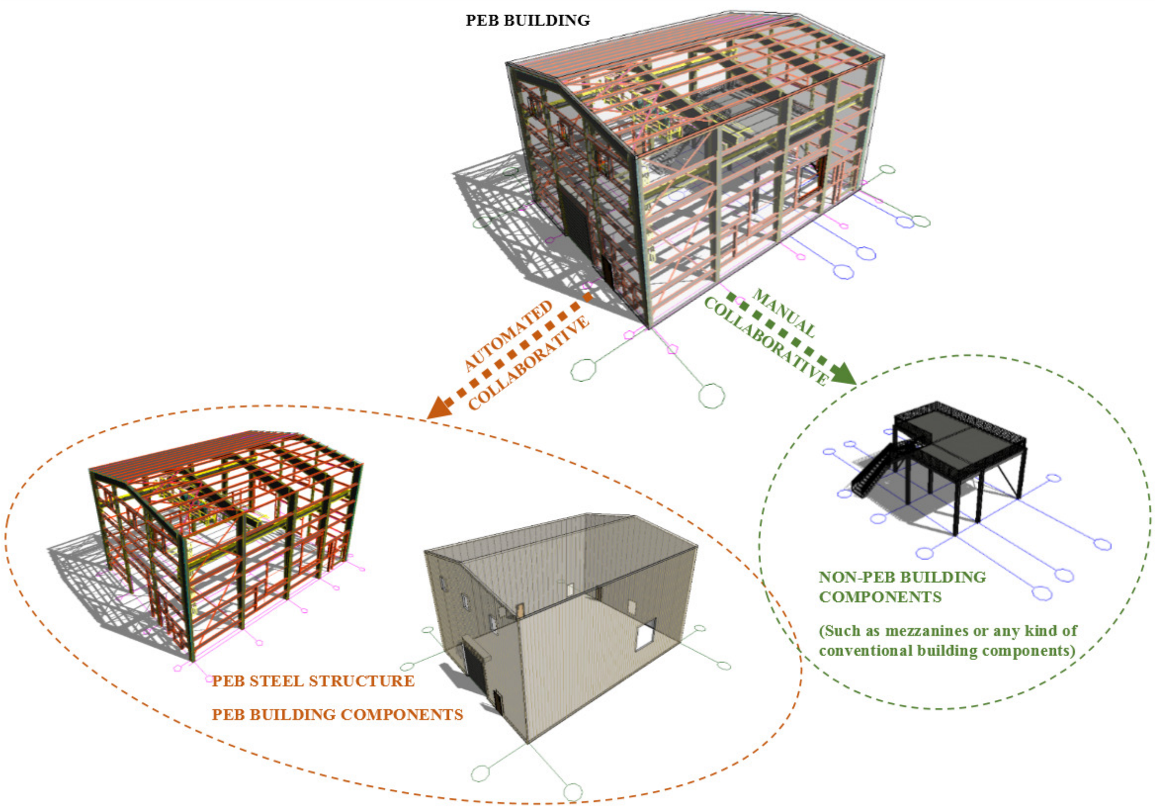

Fig. 2-14 Suggested BIM framework for PEB Separation of the process for PEB and Non-PEB elements

The main goal and focus of the authors of this article was to review the benefits, (applications), challenges, associated risks, and obstacles for the implementation of BIM for the PEB industry; in conjunction with a brief discussion on an appropriate adoption for BIM framework. Development of a practical BIM framework for PEB and its evaluation through an example project is reserved for a subsequent article.

2.6 Conclusion

This paper reviewed the benefits, (applications), challenges, associated risks, and obstacles for the implementation of BIM for the PEB industry starting with assessing the current states of BIM implementation and adoption in the construction industry in contrast with the PEB sector. A number of technical and non-technical challenges and obstacles of applying BIM in the Pre-Engineered Building (PEB) industry were identified and considered. The authors concluded that the main non-technical challenge for the application of BIM in the PEB industry comes from its 'single source responsible construction' business model. The main technical challenges are interoperability issues that arise due to the sector's custom design software and use of customized construction elements. To add to these challenges are some potential legal and contractual issues, including the potential exposure of IP.

To investigate the potential benefits and advantages of applying BIM, a PEB case study project, from Varco Pruden Buildings (VP), was reviewed over a period of three years. Multiple instances of preventable mistakes and expenses were identified over the design to erection period. The typical processes and procedures of the estimation, design, fabrication, and erection in PEB projects were examined. Some of the flaws and weaknesses of the current PEB processes that were identified included an increase in the change order costs and lack of 'project coordination' capability and versatility.

Finally, as a potential template for a BIM framework for PEB, the BIM implementation, and its processes in the Prefab construction industry were examined in contrast with the PEB industry. Full utilization of the Prefab process for the PEB sector was observed to be inappropriate due to a lack of design automation and optimization. To address this problem, the authors propose separating the process for PEB and Non-PEB components. This approach will be investigated further in a subsequent paper.

Acknowledgement

Natural Science and Engineering Research Council of Canada (NSERC) is gratefully acknowledged for the financial support to conduct this research project. The authors also wish to thank ATCO Emissions Management (ATCOEM) as a former sponsoring company. Last but not the least; the authors would like to show their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was developed.

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Chapter 3

3 Building Information Modeling (BIM) framework for Pre-Engineered Building construction project

Abstract

The effective adoption and implementation of Building Information Modeling (BIM) is still challenging for the construction industry. However, studies and reports show a significant increase in the rate of BIM implementation and adoption in mainstream construction activities over the last five years as general tools and practices mature. In contrast, Pre-Engineered Building (PEB) construction, a specialized construction system, has not seen the same uptake in BIM implementation and adoption. This paper briefly reviews the benefits and the main applications of BIM for PEB industry. Reviewing the traditional design to operation process of PEB industry, this paper explains some of the main challenges of PEB industry in dealing with the complex and collaborative project. As an effort to facilitate the implementation of BIM in PEB industry, a BIM framework adopted from Pre-fabrication (Pre-fab) industry is introduced. The Proposed BIM framework uses the similarities between pre-fab industry and PEB for the development of a framework. This framework suggests a scope separation for designing PEB building component and conventional structure. Then it automates the PEB design processes. The necessary workflows and process maps, data-exchange strategies are developed so that the PEB BIM framework is implementable. In particular, some standard extensions and two new BIM concepts, “Planar Concept” and “Floating LOD”, are proposed to overcome some technical challenges in the development of the PEB BIM frameworks. Based on all the provided technical background and illustrated processes as BIM framework for PEB, a software BIM tool implementation was developed by authors to study the feasibility and deployment of the proposed framework. The API interface and its step by step deployment procedure based on the framework are illustrated, analyzed and discussed. The authors conclude that the deployment of the proposed BIM framework for PEB could significantly address typical issues in design to operation process of the projects in PEB industry.

Keywords: Pre-Engineered Buildings (PEB), Metal buildings, Cold-formed steel system, Building Information Modeling (BIM), BIM implementation, PEB BIM framework, BIM interoperability, BIM Process; Planar Concept, Floating LOD; BIM coordinated procurement system.

3.1 Introduction

Pre-Engineered Building (PEB), otherwise known as metal building or cold-formed steel structure system is one of the fastest growing steel structural systems, used dominantly for industrial buildings but increasingly for all types of buildings. Pre-engineered steel buildings can be optimized by avoiding using excess steel by tapering the beam sections as per the bending moment's requirements on the structural elements. Also, as a standard practice, the steel structure is prefabricated in advanced robotized shops and then transported to the site where it is rapidly erected (e.g. typical erection times are less than 6 to 8 weeks[1]). PEB has some advantages beyond reduced construction time and associated cost efficiencies such as flexibility of expansion, large clear spans, better quality control processes, low maintenance, compatibility with energy efficiency roof and wall systems, sustainability and single source responsibility. All these advantages have led to the PEB structural system to be used not only in industrial building applications but also in commercial, institutional, recreational, agricultural, aviation and military purpose buildings [1–3].

Building Information Modeling (BIM) involves the generation and management of digital representations of physical and functional characteristics of a construction project [4]. Use of BIM has widely increased over the past decade by architects, engineers and construction practitioners [5]. Despite the increase in the usage of PEB construction [6], the authors have observed that BIM has not made the same inroads into the PEB industry as in other segments of the construction sector [7–9].

BIM adoption in the PEB industry, similar to other industries, would require a adaption of the existing practices to utilize BIM over part or throughout the entire project lifecycle [10]. This paper proposes that BIM would be of benefit to the PEB industry if approached with an appropriated developed comprehensive BIM framework. However, performance and applicability of the proposed framework need to be examined and evaluated based on developing and applying BIM based software to the PEB industry.

This paper briefly reviews the benefits, risks and challenges in BIM implementation for the PEB industry and then proposes an overall BIM framework for practical implementation. Part of this proposal include approaches for addressing some of the main technical issues in the development of the framework such as interoperability problems, automation in BIM modeling process and customization challenges. Based on this framework a software BIM API has been developed for implementation of BIM in PEB industry. This API software follows the proposed BIM framework to automate the process of the design and to present an example implementation, which is then reviewed to identify benefits, remaining challenges and applicability of BIM for the PEB industry.

3.2 BIM implementation in PEB

In order to conduct research on BIM implementation in PEB industry, common practices and existing workflows in general PEB industry in North America were studied. To investigate the potential benefits and advantages of applying BIM, a PEB case study project and a PEB industry major player -Varco Pruden Buildings (VP) [11] - design to operation processes, were reviewed over a period of three years. The results of the study on BIM implementation in PEB industry were presented in this thesis ([12]-Chapter 1) and are briefly recapped here.

3.2.1 PEB industry's most practiced process and workflow

3.2.1.1 General Process and challenges

In any project delivery method, PEB manufacturers work as structural designers and developers directly or mostly working closely with a structural designer party in the contract. The structural designer party is mostly known as “developers” or “dealers.” The design process is done using PEB proprietary non-BIM software with some CAD capabilities. The whole PEB design process has been developed based on specific proprietary products and processes that each PEB manufacturer has. Hence, the entire process from design to erection will be handled by specific stakeholders. This method in the PEB industry is known as “single source responsibility” [3]. On the positive side, this approach can increase the speed of design, fabrication and erection of a customized building, but on the negative side is quite limited and can become very challenging where interaction with other project design stakeholders are required. In other words, the non-BIM process for PEB industry is to some extent non-collaborative, which can cause some major issues. An overview of the PEB design process and collaboration challenges are illustrated in Fig. 2-8 in Chapter 2 of this thesis.

3.2.1.2 PEB Building design and documentation process

Although the traditional approach for designing PEB buildings by manufacturers has its drawbacks, its advantage is its commonly automated steps which make it very effective and efficient, at least for non-collaborative projects. Irrespective of the difference in usage or geometrical properties of PEB buildings, they can be classified based on basic shapes or combinations of those basic shapes. Therefore, industry has developed a common algorithm for the design process of a PEB building. The software interface and common workflow/algorithm developed by PEB industry of two mainly used PEB software (VPCommand [11] and MBS [13]) are shown in the Fig. 3-1.

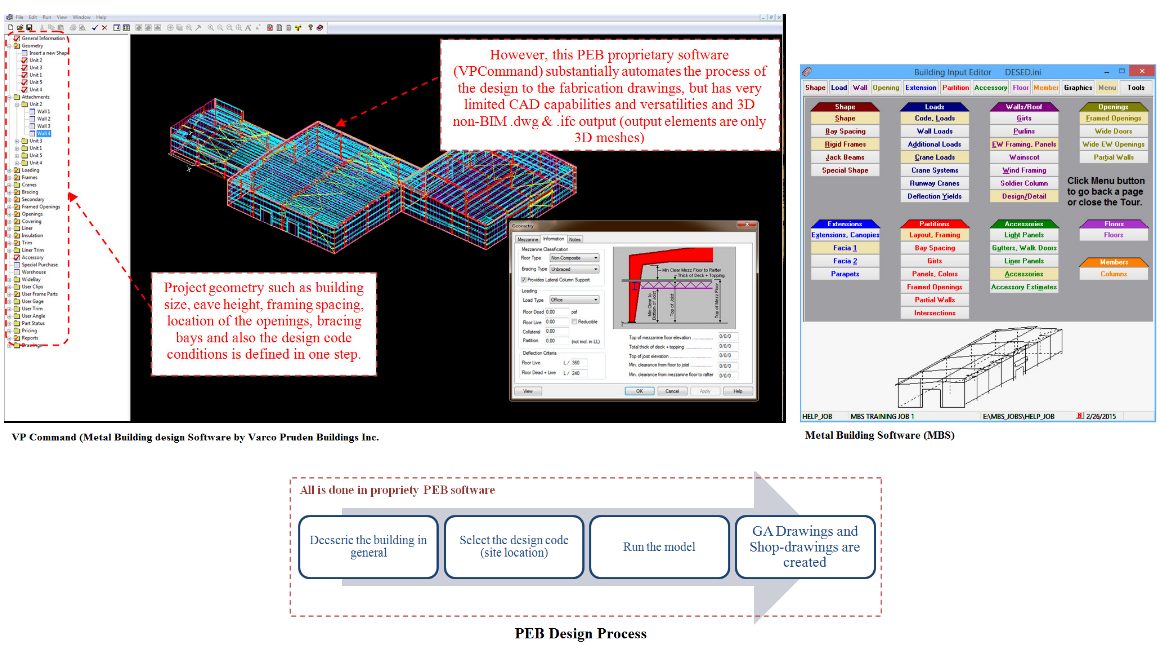


Fig. 3-1 Commonly used workflow/approaches for PEB building design developed by industry - two example software[11–13]

However, as identified in ([12]-Chapter 1) and above, the current process is not efficient nor effective for more collaborative and application sensitive projects, which has led to the development of the proposed BIM framework.

3.2.2 Importance and applications of BIM for PEB industry

The main source of benefits usually attributed to BIM is its support for collaboration through streamlined, unambiguous communications for design, construction, and operations. BIM can help PEB building owners by visualizing the outcome of projects. Also, BIM models with a high level of development (LOD) can be used as an asset for facility management during the operation of the buildings. As mentioned PEB building are used widely for industrial projects containing sensitive mechanical and electrical components. Therefore, having a BIM model of the building system can be extremely useful at the operational stages ([12]-Chapter 1).

In contrast, the PEB industry is typically using a "single source responsible" process for design, Pre-fabrication, and erection of a building. Using this traditional PEB process, a project may be faced with some problems and difficulties in communication between design disciplines; change orders can become costly, and manual/paper based design coordination can become extremely difficult due to limitations on effective data exchange. BIM can significantly help PEB process by increasing the early stage design coordination through a collaborative 3D coordination environment, by improving information exchanges capabilities using 3D models ([12]-Chapter 1).

3.2.3 Challenges and Obstacles in implementation of BIM in PEB

Some challenges and obstacles need to be addressed before these advantages, and applications of BIM can be realized for the PEB industry. These challenges can be categorized into two main groups: "technical" and "non-technical" challenges. The technical challenges are mostly around interoperability issues, and lack of a BIM PEB design tools. (Unfortunately, there is also a lack of drivers for current PEB design tool authors to incorporate BIM.) The non-technical issues include; establishing new processes and changing old industry habits, the existing business development methods for PEB industry, the lack of PEB industry awareness of BIM and potential risks and liabilities in adopting BIM in PEB industries ([12]-Chapter 1).

3.2.4 Risk associated with BIM implementation PEB

Using BIM in a project may raise important contractual issues associated with project responsibilities and risks, contractual indemnities, copyright, and use of documents that are not addressed through the standard industrial contract forms. These issues, potentially, are major concerns for the adoption of BIM in industries. Associated risks can be grouped into two main categories; Risk allocation and Intellectual property rights. There are legal (contractual) and risk allocation issues involved with BIM implementation in any industry, as non-technical challenges. The first allocated risk is the insufficient determination of ownership of the BIM data and the need to protect it through copyright laws and other legal channels. To prevent a disagreement over copyright issues, the best solution is to stipulate in the contract documents ownership rights and responsibilities. Another aspect is that sharing high LOD BIM models of the PEB building components including the steel structure with the other project stakeholders (e.g. case dealers and owners) will always bring up some related intellectual property issues. High-level LOD 3D models can be used for extraction of critical data such as shop and fabrication drawings or allow for reverse engineering of designs. Subsequently, the net profit of the PEB manufacturer could be at risk. Thus, the PEB industry is traditionally not interested in sharing any 2D or 3D data with higher levels of accuracy and development ([12]-Chapter 1).

3.2.5 PEB industry Vs. Pre-fabrication industry

An efficient approach for a framework development for a specific industry is to utilize an existing framework for the similar industry as a template. Pre-fabrication (Pre-fab) industry has a high degree of similarity to the PEB industry due to their shared dependency on offsite fabrication and modularization. Fig. 3-2 highlights some of the similarities and the main differences between these two industries.

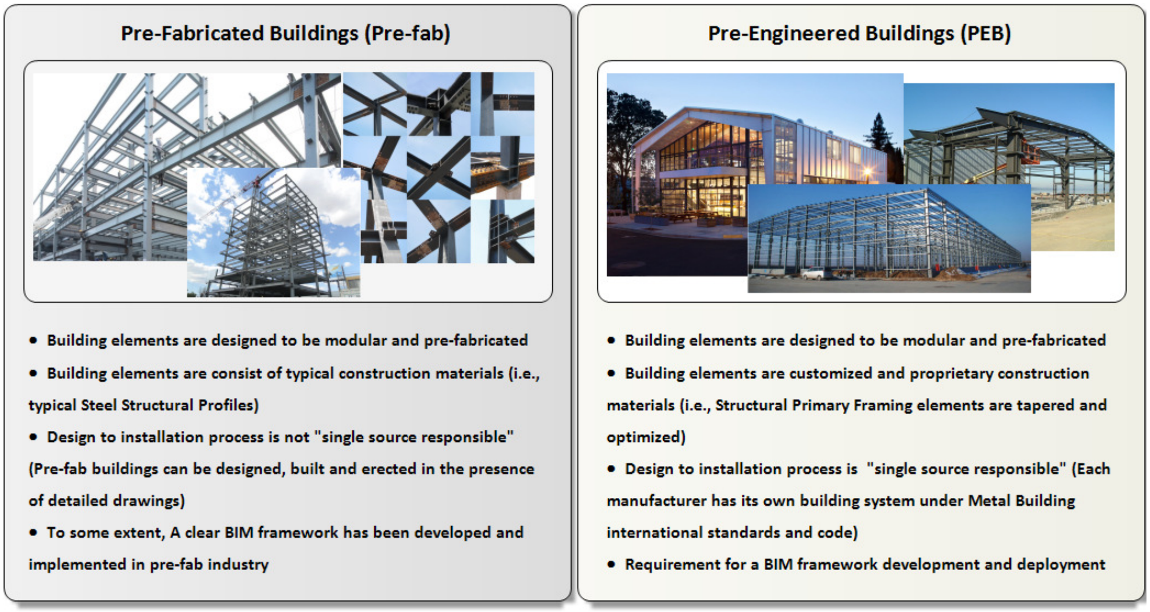


Fig. 3-2 Pre-fab industry vs. PEB industry ([12]-Chapter 1) &[13-18]

Although there are similarities in the nature of the both industries, there are some significant differences in the design processes followed by these two industries. Some of these differences are shown in the Fig. 2-12 in chapter 2 of this thesis. Prefab design and fabrication is not dependent on any dominant market players, as is the case for PEB, and the process of the design is more flexible. In addition, the Prefab industry uses standard manufactured steel profiles, which can be easily sourced. All these features have made BIM well-suited to the sector and have led to higher levels of BIM adoption in prefab industry over the past decade[9]. It is observed that due to the similarities in the nature of the both systems (regarding the prefabrication processes), some attempts have been made by several major BIM software vendors such as Autodesk and Bentley, to design PEB buildings using the Prefab process[19,20] although their approaches lacked the automation usually inherent in the PEB design process.

3.3 Challenges in development of a BIM framework for PEB and proposed resolutions

Before the main proposed processes and workflows for a PEB BIM framework are discussed, some resolutions for the main challenges of such a development are suggested here.

3.3.1 Resolution of system interoperability problems

CIMsteel Integration Standards Release 2 (CIS/2) offers a practical data-exchange protocol and standard as a resolution for BIM interoperability issue [21] for structural steel. Using the CIS/2 standard to bring more versatility to existing PEB software systems, such as VPCommand, to enable them to exchange the data with other external applications in integrated workflows during the design and construction phase of a PEB project. CIS/2 translators can be used to transform the data for such exchange process as is shown in Fig. 3-3.

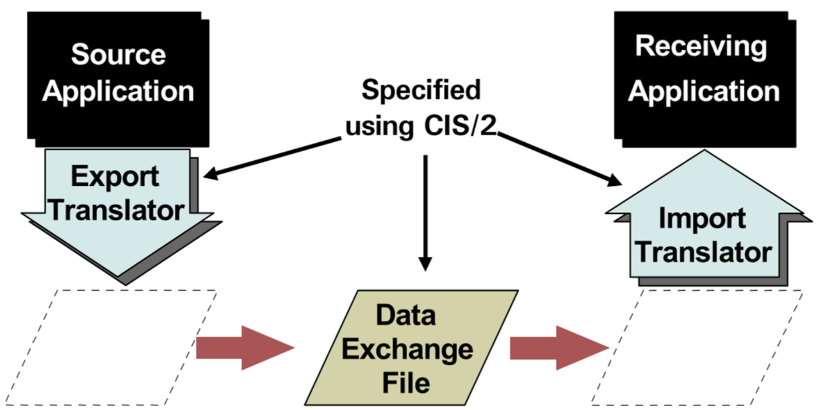


Fig. 3-3 Data exchange process with external application in CIS/2[22]

Traditionally, most of the representational standards such as IFC describe the linear fixed depth and profile structural members without challenges. However, structural members in PEB system have varying depth with undefined structural nodes which make the description process difficult. The difficulties describing these variations can be considered as one obstacle for establishing data exchange mechanisms for PEB models. CIS/2 under the section 8.3.7 (part_prismatic_complex_tapered Entity) [22], introduces an existing standardized method to described tapered elements (illustrated in Fig. 3-4). It is suggested to utilize this method to solve the model description issue in any required data exchange activities.

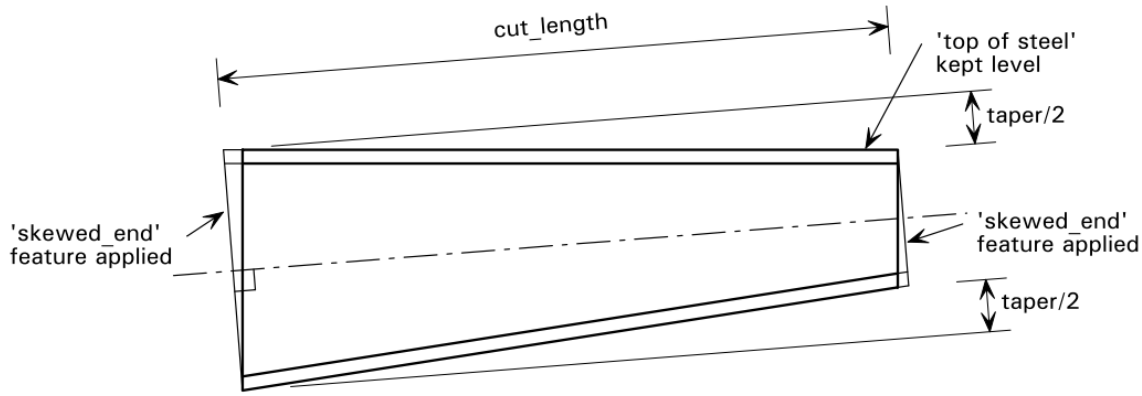


Fig. 3-4 defining a part with varying a depth (tapered element) in CIS/2[22]

3.3.2 Automation and customization for BIM system

3.3.2.1 Limiting BIM 3D modeling capabilities

As discussed earlier, the traditional PEB design process is quite efficient regarding the integration of modeling process, structural design and representing the results and documentation for standard structures (Fig. 3-1). Basically, this approach has automated the design to documentation process for standard PEB buildings. As a reasonable act, traditional model development approach developed by PEB industry can be utilized for BIM framework development due to its efficiencies. The PEB process starts with the end user describing a building geometry by selecting its initial shape. This building shape must be simple framing PEB enclosure or a combination of simple enclosure shapes. This approach is generally practical for PEB buildings as their typical shapes are simple and relate well to their applications. However, there are a number of occasions where desired "customization" may not work properly. For example, if a simple shape PEB building needs minor modifications in its shape, it can be extremely difficult or impossible to enter this information into the design software as all existing PEB design tools lack 3D CAD base interactive modeling environments. Another example could be when the project calls for a non-typical shape for a PEB building. This mostly occurs when an industrial project is inside a residential area imposing visual requirements on the design. These challenges are commonly addressed in industry domains that leverage BIM's building element level modeling capabilities in their design authoring systems. Unfortunately, the cost of the flexibility of BIM modeling is reduced efficiency in comparison to the traditional automated PEB approach regarding the modeling process, structural design and generating the results and documentation. What is the solution?

3.3.2.2 "Planar Concept" as a resolution for customization problem

A number of different approaches were tested to find the best solution for creating intelligence for PEB building elements in BIM design authoring environment using an automated process. Results suggested that grouping and categorizing similar elements in BIM design process could support automation. However, placing 3D elements in the design environment by referencing some snap points around their geometry will generally cause some discrepancies between the position/location of physical 3D elements and analytical elements (such as lines, nodes, planes, etc.) used for the structural analysis. This matter could undermine any integration and automation for design to documentation process PEB buildings.

What if a group 3D models (of building elements) in BIM environment could be developed while all the physical and non-physical sub-elements could be referenced to a unique reference plane (Fig. 3-5)?

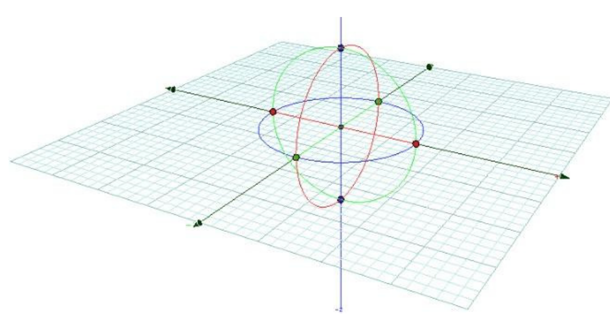


Fig. 3-5 A hypostatic 2D reference plane[23]

Traditionally, in BIM design development, reference planes are used to assist in the placement of 3D elements in 3D model environment while using 2D controllers [24].

As it is shown in Fig. 3-6; Planar Concept proposes a new BIM element classification regarding their structural applications; then it uses reference planes a controller to define an intelligent/logical relationship between elements.

An implementation of Planar Concept for BIM model development process, not only supports the required automation in the BIM process for implementation in PEB industry, but also introduces some new concepts and proposes a new approach for the BIM design process (Shown in Fig. 5-15 in chapter 5 of this thesis). This concept can be deployed for creating automation generally in other construction industries as well.

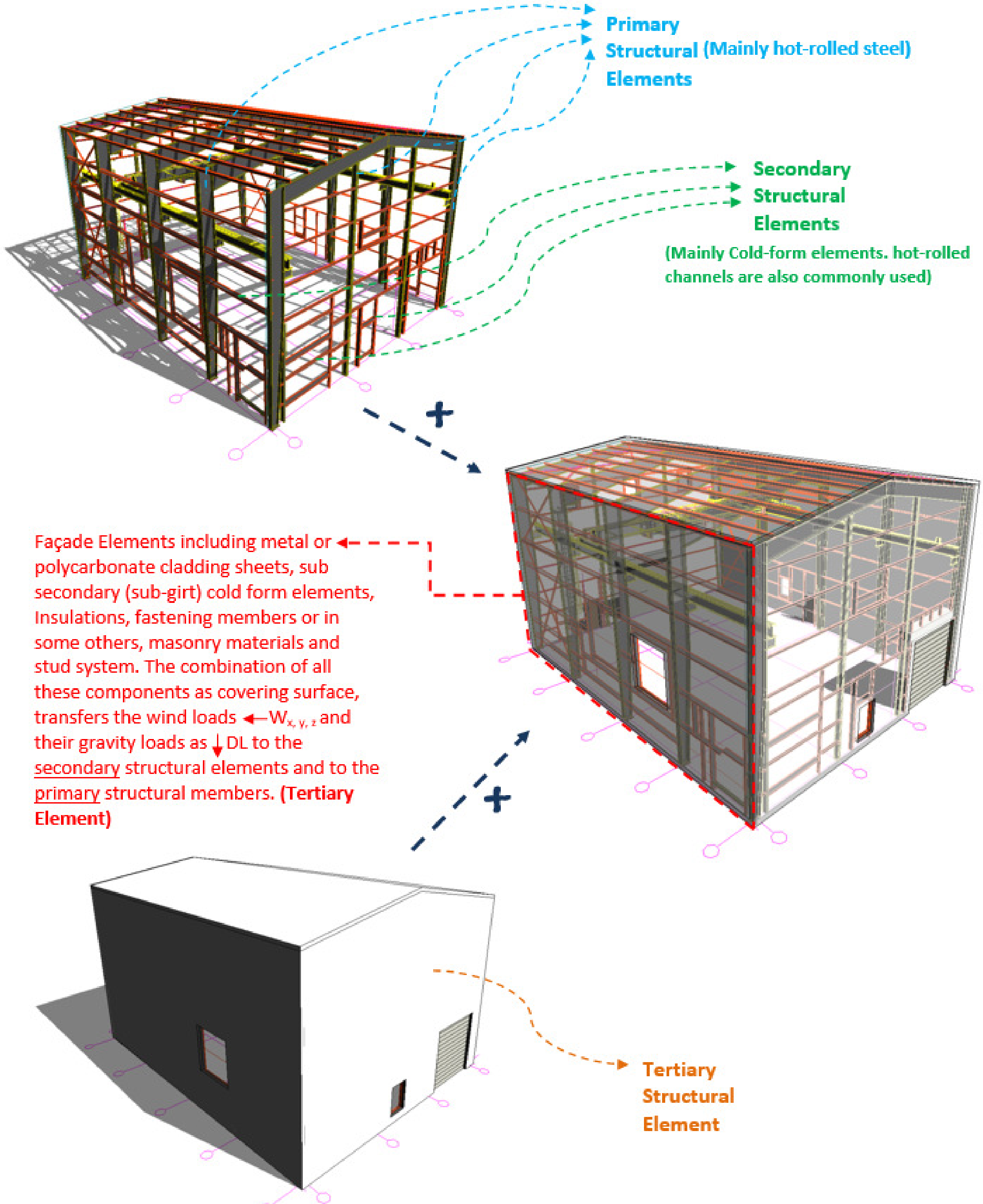


Fig. 3-6 Planar concept introduces a new classification for BIM elements([12]-Chapter 1)

A more comprehensive discussion and illustration of the proposed "Planar Concept" are out of the scope of this article but will be published separately ([12]-Chapter 5)

3.3.3 Challenge of BIM Level of Development (LOD)

3.3.3.1 High LOD models in PEB traditional process

Selecting the LOD or proper model development level to match a project's application and requirements is still a challenging matter in BIM. There are two main challenges. First, identifying a LOD which is sufficient for most of BIM applications for the project. Second, actually developing a model to that degree, regarding the time and cost associated with such a development. Traditionally PEB design tools can develop a CAD 3D model to an effectively equivalent level to LOD 300 (considering an approximation for different LOD classifications) and higher in an automated process. This feature is considered as one of the main selling points for these tools to date. However, this development is an outcome of an automation process, which brings a number limitations, as previously identified. The main challenge in developing a BIM framework for the PEB industry is to identify a LOD level which could compare favorably with the traditional process application, as well as be feasibly produced by an automated process.

3.3.3.2 Optimum LOD and Floating LOD concept for PEB BIM framework

As part of the research on implementation of BIM in PEB industry, the impact of LOD levels on BIM applications and drivers were studied using some respected international surveys. An analytical modeling approach was used to define a hypothetical point as an optimum level of development. As a result, LOD 300 was suggested to be an acceptable approximation for an optimum LOD point which can support most common BIM applications([12]-Chapter 4).

As it was indicated earlier, an automated process for model development using BIM is an objective for this research. Developing a higher LOD 3D model is a time-consuming process. Moreover, as a BIM model gets more and more 3D components, managing this model becomes more and more difficult for both computer and human operator. Smaller scale errors and mistakes can become very difficult to be observed and managed in a model. Also, beyond a certain level of LOD, the requirement for computer processing and graphic capabilities increases significantly.

The idea proposed here is to deal with all building elements in a similar way to the modeling approaches for existing intelligent parametric families such as doors and windows. Initially, when modeling and placing a door or window the operator only inputs basic dimensional and relative position information. The design tool itself uses those numbers to generate specific elements and their geometry based on generic parametric family descriptions and places them in the model. Neighboring model elements will also be updated or generated as appropriate (e.g. making voids in walls for the windows and doors to occupy). However, applying this process to large scale building system elements building elements requires more considerations, such as database management issues. Most of these database issues are regarding the providing the proper portals and panels in BIM software interface for interaction with the database without overwhelming the end user. The proposed Floating LOD concepts propose making it possible to automate generating high LOD models (i.e. all primary, secondary and tertiary elements fully specified) from lower LOD models (i.e. generic or system level descriptions of walls and windows without their constituent components) and reverting back again. Most design specification would be done at the low-level, and then automatic algorithms would convert more generic design descriptions into higher LOD models, complete with properly proportioned secondary and tertiary elements, while maintaining links back to their lower LOD description to facilitate reverting to more basic models sufficient for analysis or adjustment of broader design constraints. The goal is to provide the appropriate LOD level models as required. The name "Floating LOD" comes from the nature of this ability to easily transition between the different LOD model levels. Fig. 3-7 illustrates the Floating LOD concept processes and benefits.

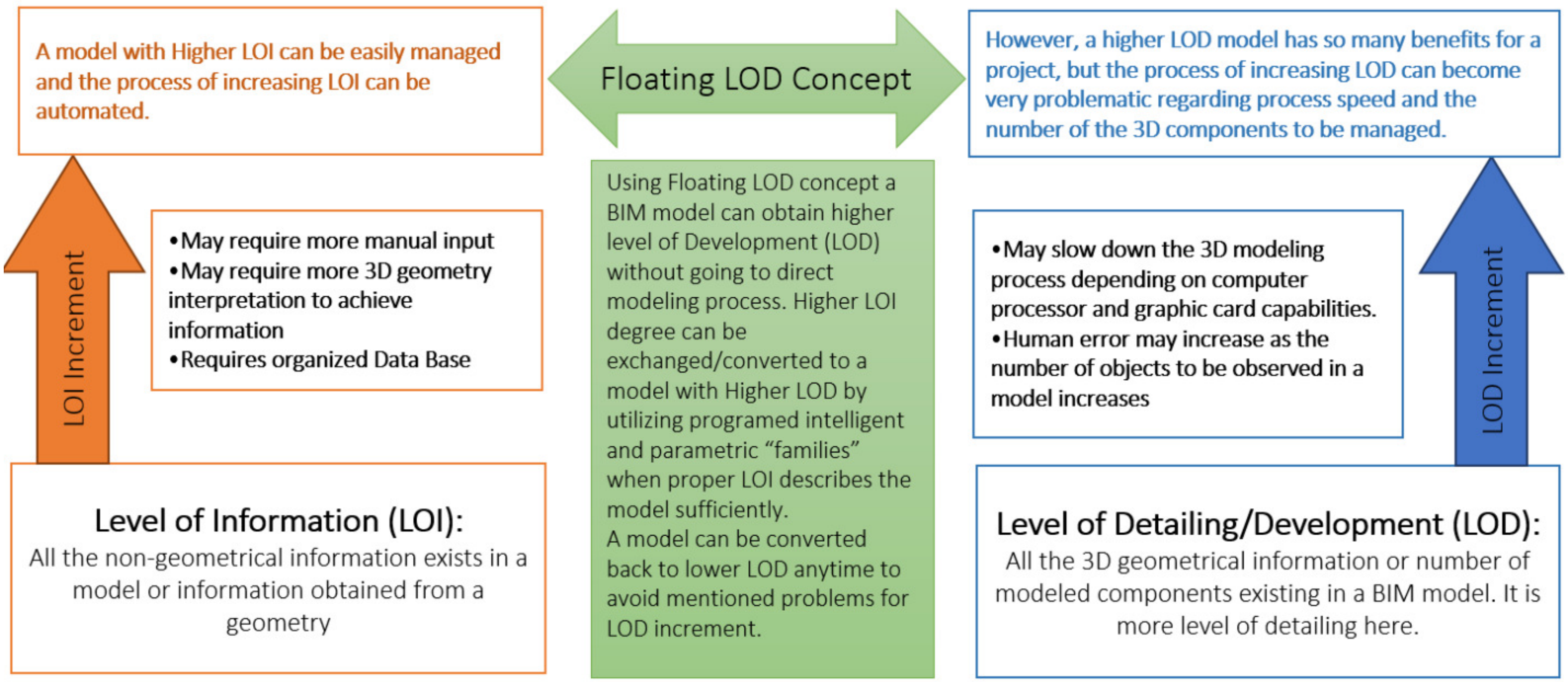


Fig. 3-7 Floating LOD concept([12]-Chapter 1)

A comprehensive introduction of the Floating LOD concept is not in the scope of this paper and will be left to future publications.

3.4 BIM Framework for PEB industry

3.4.1 BIM Process; adoption from Prefab industry

As it was described earlier one of the most important advantages of the PEB over other structural systems is its automated, single source and time-saver (efficient) process. To maintain the advantage of automation in a BIM process for PEB, an adopted prefab BIM process is required. Thus, the current system for specifying design requirements which has been developed by PEB industry would need to remain in use although a transition from 2D modeling to 3D modeling would be required. Using this approach all the PEB structural (including primary tapered frames, secondary cold-formed girts and purlins, all the connections, etc.) as well as none-structural elements (including metal siding sheets/panels, insulations, barriers, etc.) could still be automatically designed using the PEB process and tools as illustrated in Fig. 2-12 in chapter 2 of this thesis. The user only describes the general building characteristics. To deal with other conventional/non-PEB building components (such as mezzanines, structural supports for equipment, etc.), they should be separately processed using the standard prefab BIM design process illustrated in Fig. 2-12 in chapter 2 of this thesis. (where very detailed input is necessary for each element). This dual process approach and general BIM workflow using this approach are illustrated in Fig. 3-8. The final designs from each process could be kept as separated or to be integrated and incorporated into a final BIM model using BIM interoperability features.

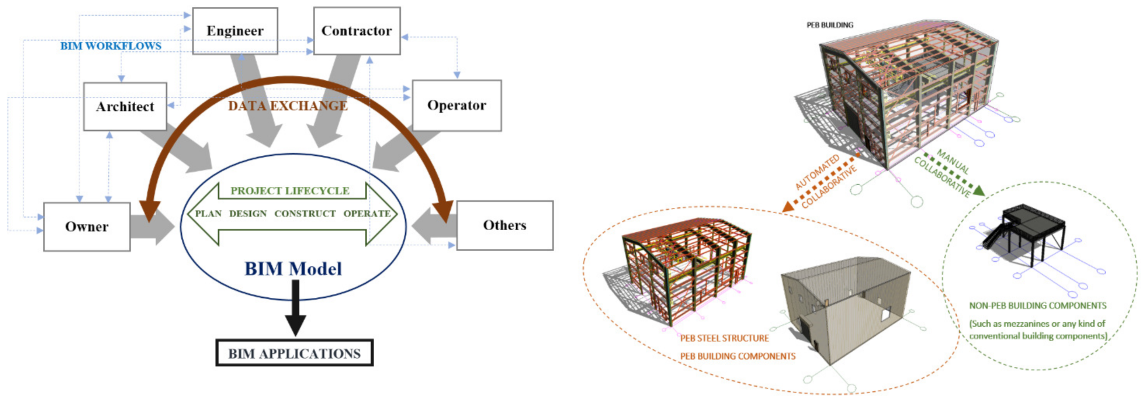


Fig. 3-8 BIM framework process for a practical workflow and collaboration ([12]-Chapter 1)

3.4.2 BIM Workflow, Collaboration Process Map, and Data-exchange

Since separating the PEB and non-PEB elements is the key point in the process a practical workflow for BIM base collaboration for PEB industry is still needed. Fig. 3-9 illustrates a proposed collaboration and data exchange workflow between project stakeholders during the different phases of a project lifecycle. This process and workflow is general and can be used in any collaborative project delivery methods such as Design-Bid-Build (DBB) and Design Build (DB). To suggest a generic workflow/process map, the construction party which is involved in the design and development of the PEB building in collaboration with PEB supplier is called "developer" (e.g. general contractor, consultant or GC) in Fig. 3-9.

3.4.3 Risk mitigation

As it is described in Fig. 3-9 the entire process of data exchange and workflow between different disciplines in planning and design phase is performed using only a lower level LOD model. Therefore, the model is not developed to the level which fabrication and shop drawings data could be extracted from it (higher level of LOD) until the construction phase and then only by PEB supplier/manufacturer. This intentional control of information detail in the workflow could help the PEB supplier and developers as dealers to protect their rights and to mitigate the risk in data-exchange which was explained in earlier chapters of this paper as a potential risk issue.

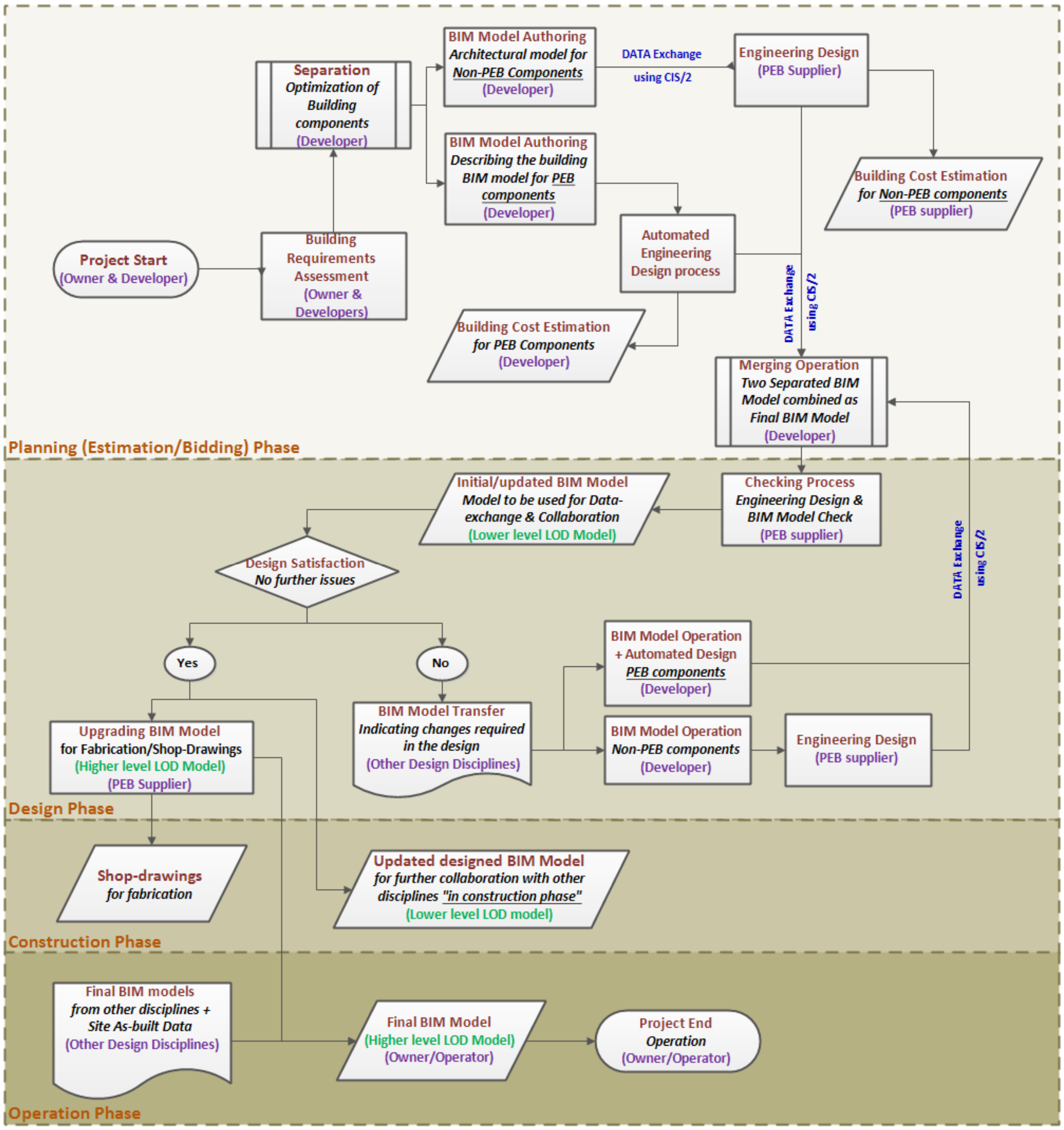


Fig. 3-9 BIM Collaboration and Process Workflow

3.5 Evaluation of the framework for PEB industry

To evaluate the proposed framework and introduced concepts, all BIM processes should be implemented through a BIM design authoring software. A working software application, using existing design software APIs was developed to perform an assessment of the proposed framework.

3.5.1 API software based on the framework

The developed PEB design tool uses Autodesk Revit GUI to interact with users and automate the design and modeling processes of a PEB building. This tool performs architectural model development and structural analytical model development using pre-designed PEB structural and nonstructural Autodesk parametric 3D objects (families). The developed algorithms based on the defined processes in the proposed framework were coded and developed using Microsoft Visual Studio (.Net) using existing functions and libraries offered in Autodesk Revit Software Development Kit (SDK). The software command icons were added to Autodesk Revit as a separated "Ribbon". The process used to develop the software, design the PEB specification interface on Revit GUI, and to add a new Ribbon element to Revit are shown in Fig. 3-10.

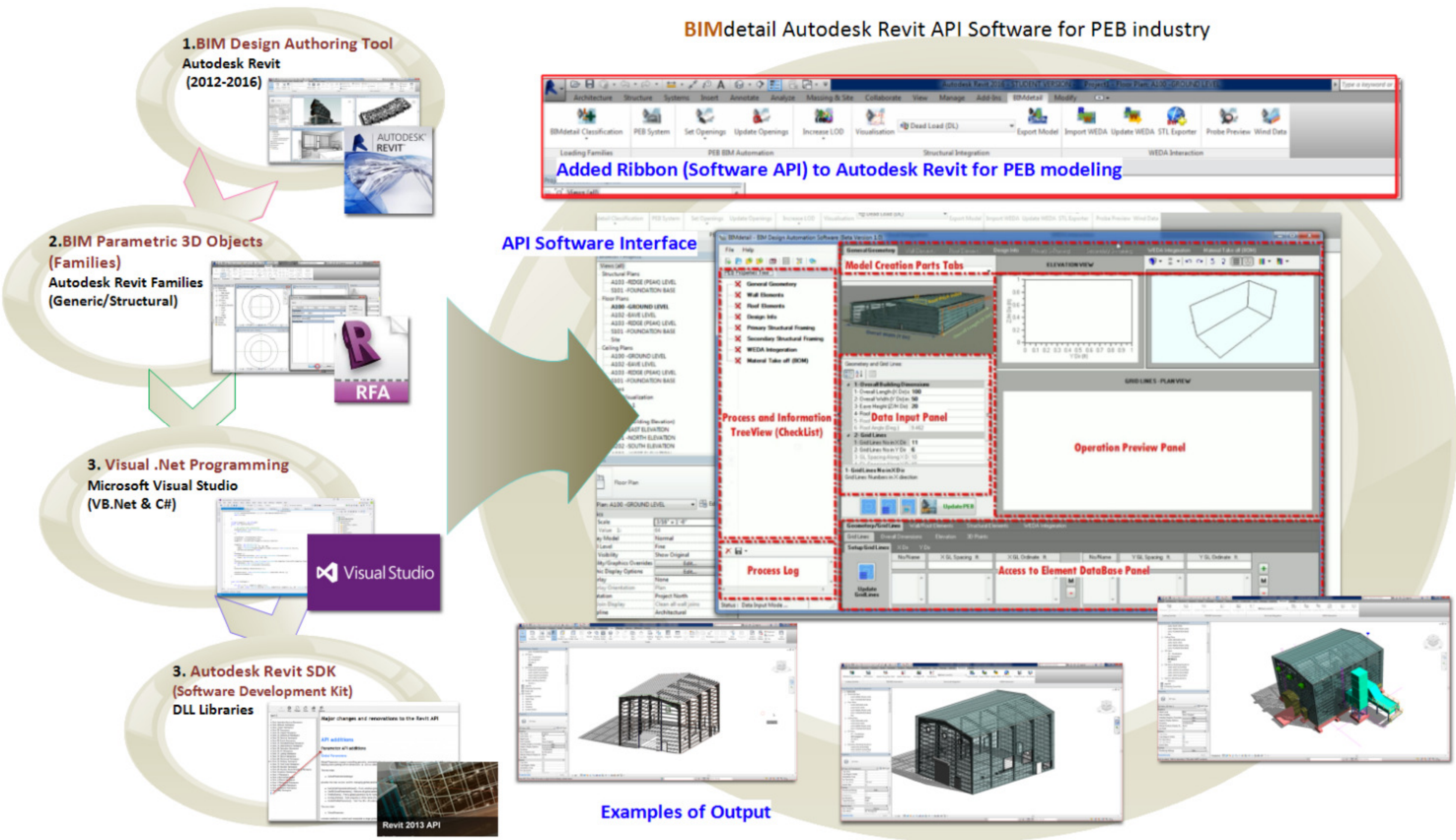


Fig. 3-10 Software tool developed by authors to evaluate the BIM framework for PEB

3.5.2 Example PEB project

To evaluate the proposed framework after the software development, the performance of the software on the design of an example project was tested. The example project was a real industrial PEB building which had been designed and developed using the traditional non-BIM tools and PEB process. The design of this 21m x 16m x (11.53m Eave Height) Gas Compression Station was done in the absence of any BIM model for PEB structures, the building enclosure, and a collaborative environment.

As it is shown in Fig. 3-11, the building owner and general contractor developed comprehensive BIM models for all mechanical and electrical components of the building which were never used (for the development of the PEB building) due to the absence of a collaborative workflow and data exchange capabilities. Note that the rough 3D enclosure model which is shown in Fig. 3-11, is a low LOD CAD conceptual model developed by the owner to describe the required building and had no value for design in further steps.

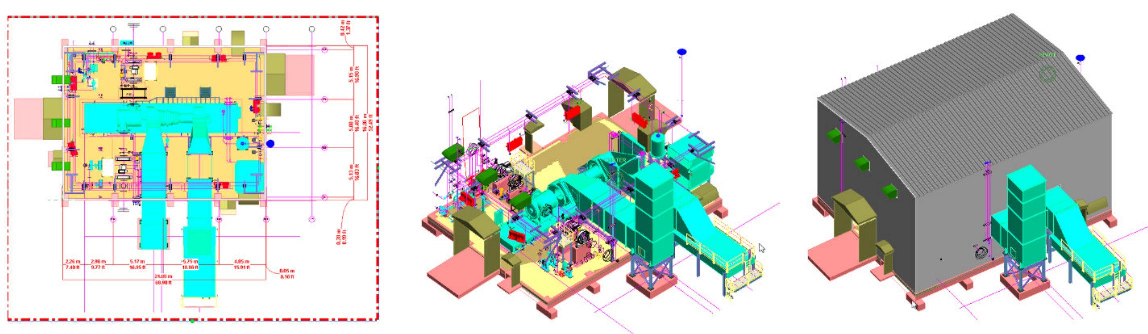
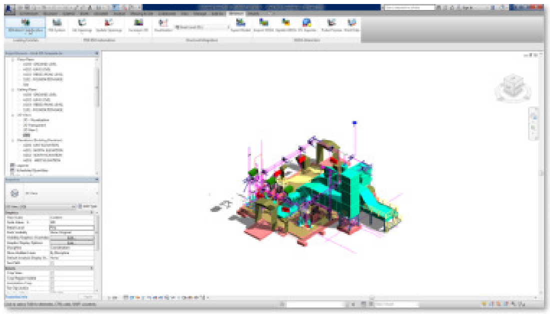


Fig. 3-11 Example Project with existing BIM model for all the mechanical/electrical building components but the PEB structure and building enclosure

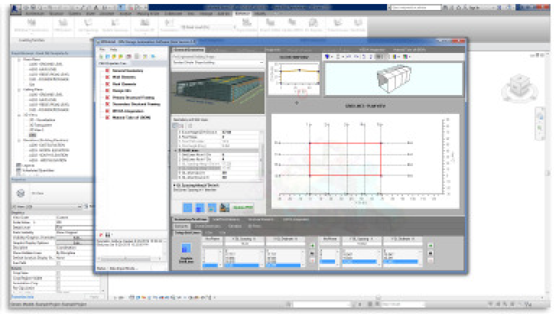
Although this PEB enclosure has a relatively simple shape, it is still considered a highly sensitive project due to its critical application. Also, this project was a principally collaborative project constrained to a very congested area with mechanical and electrical equipment interfering with and penetrating the new design elements. It is worth mentioning that the real project had a very compressed time-frame and a tight schedule for construction as a critical operational gas compression station. Also, the owner was keen to have the best operation and maintenance manual resources for repair and emergency actions.

3.5.3 Illustration of the design process using the proposed framework and developed software

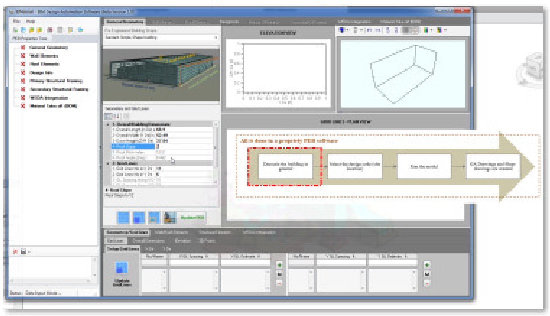
Unlike the traditional approach for designing the PEB buildings, the developed tool uses a collaborative approach using the developed framework. This collaborative approach begins with incorporating accurate (higher LOD) BIM models from other disciplines into the design environment. Then it uses the software interface to step through the proposed workflows. The BIM model and design development steps and process through the API interface are shown in Fig. 3-12.



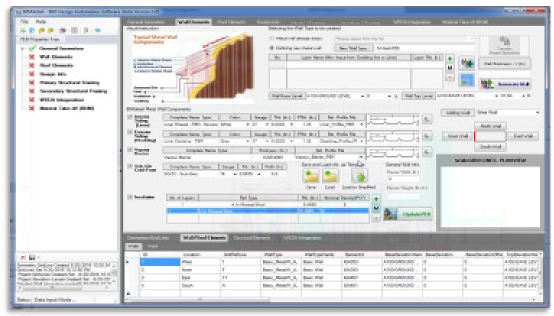
STEP 1: Starting the design process on a collaborative environment and Building the PEB 3D model on Existing BIM models of Mechanical/Electrical equipments



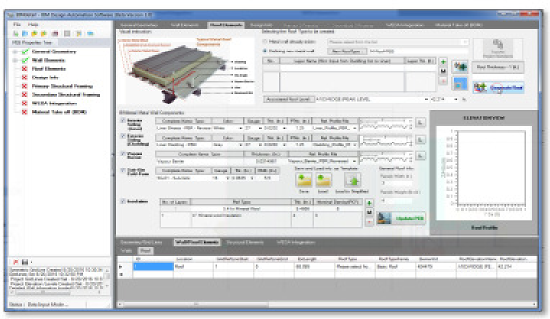
STEP 2: Loading the API software on Autodesk Revit GUI



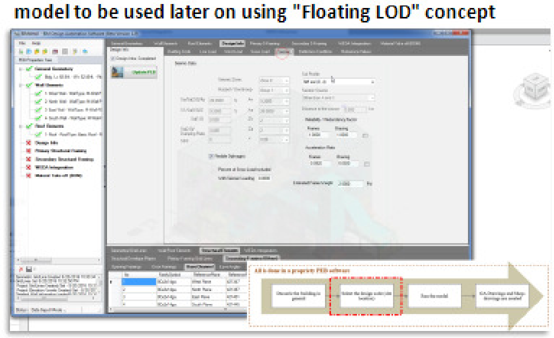
STEP 3: Describing the PEB building by inputing the geometry properties and building Grid lines



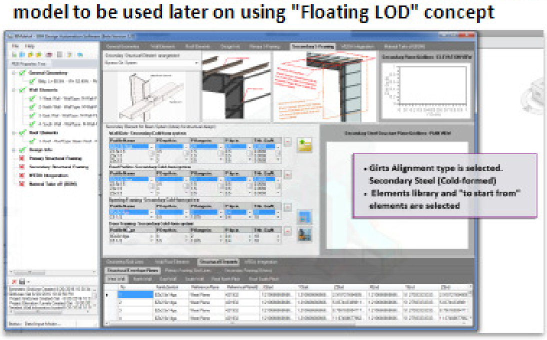
STEP 4: Inputting/Loading/Saving PEB wall system properties. The input information at this step can increase LOI of the BIM model to be used later on using "Floating LOD" concept



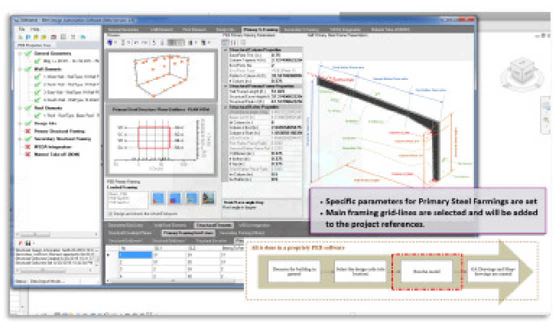
STEP 5: Inputting/Loading/Saving Roof system properties. The input information at this step can increase LOI of the BIM model to be used later on using "Floating LOD" concept



STEP 6: Structural Design criteria and specifications are input at this stage for internal structural design process



STEP 7: Secondary structural elements design criteria is input here using the BIM structural components loaded in Revit



STEP 8: Primary structural elements design criteria is input here (different manufacturer can customize their main frames at this stage

Fig. 3-12 Illustration of the model development process for PEB building

Initially, the software tool develops the enclosure models (all the walls and roofs) as per inputs in initial steps. Also, it accurately adds all the BIM 3D grid lines and project levels for the building description to BIM design interface to base subsequent positioning of elements on.

Based on PEB (Metal Building) international standard and design codes, building structures and components are analyzed and design separately. Main primary framings are treated such as 2D hot-rolled/3-plate frame elements, then the performance of the whole framing system is assessed regarding deformation/movements and stresses[25]. In later steps, other secondary elements such as girts, purlins and framing elements which are mostly cold-formed elements are analyzed and designed separately and regarding their loading tributary area. Hence the proposed BIM collaborative process for PEB starts by identifying all the obstructions and probable collisions (other disciplines equipment) clashing with the initial primary framing layout. At this stage, the PEB BIM design developer can move the main structural framings regarding mechanical/electrical/architectural obstructions (i.e. openings, doors, pipes, ducting, cable trays, etc.), or visually communicate to other disciplines (using a BIM review software) to find easier or possibly cheaper approaches. After analysis, design and establishment of the main framing elements (as per input criteria in STEP 8 Fig. 3-12), the software designs the secondary elements framings layout. The final design input of other disciplines are incorporated using the criteria input in STEP 7 (Fig. 3-12) and usually requires several trial and error explorations of possible solutions. This process is done using a collaborative approach by laying out the openings manually (or automatically using interface and clash detection process; not yet implemented in this tool) at the locations of the probable clashes and openings (using a rough opening size criteria). Then all the secondary elements are placed and designed in the none-clashing locations. This process using PEB BIM software is illustrated in Fig. 3-13.

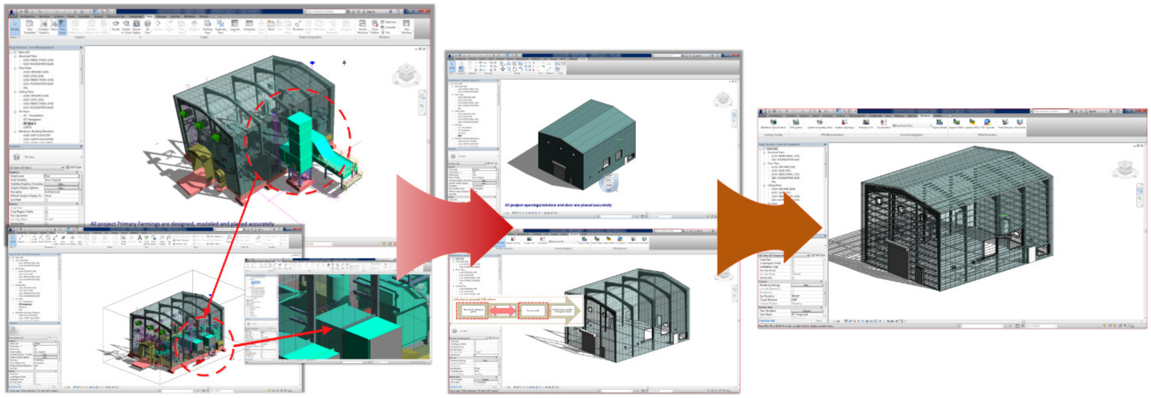


Fig. 3-13 Illustration of collaborative process for designing the PEB building opening and structures regarding Architectural/Mechanical/Electrical obstructions

The proposed “Planar Concept” not only helps PEB BIM framework to overcome some of the interoperability problems, but it also could assist in automating existing BIM processes used by the general construction industry.

The planar concept idea targets supporting fully automation of structural/analytical models in parallel with the development of the architectural BIM model. Existing approaches can often place represented analytical elements such as beam/columns “stick members” and nodes in inappropriate relative geometrical positions[26]. This proposed process introduces three different classifications of building elements based on their role in models. The software places the analytical model elements relative to the predefined reference 2D planes([12]-Chapter 5).

The tributary area for each element is automatically calculated using a geometry base meshing and dead load and other material related loads are calculated and transferred to the analytical model. This process also uses some intelligence obtained from the classification based sorting. The process and outcome of the utilization of planar concept in PEB BIM framework are illustrated in Fig. 3-14. (Note that however the design process of structural bracing system -bracing rods- and their models are not shown in the pictures, but they are developed in a similar approach to the secondary framing by finding non-clashing/clear bracing bays)

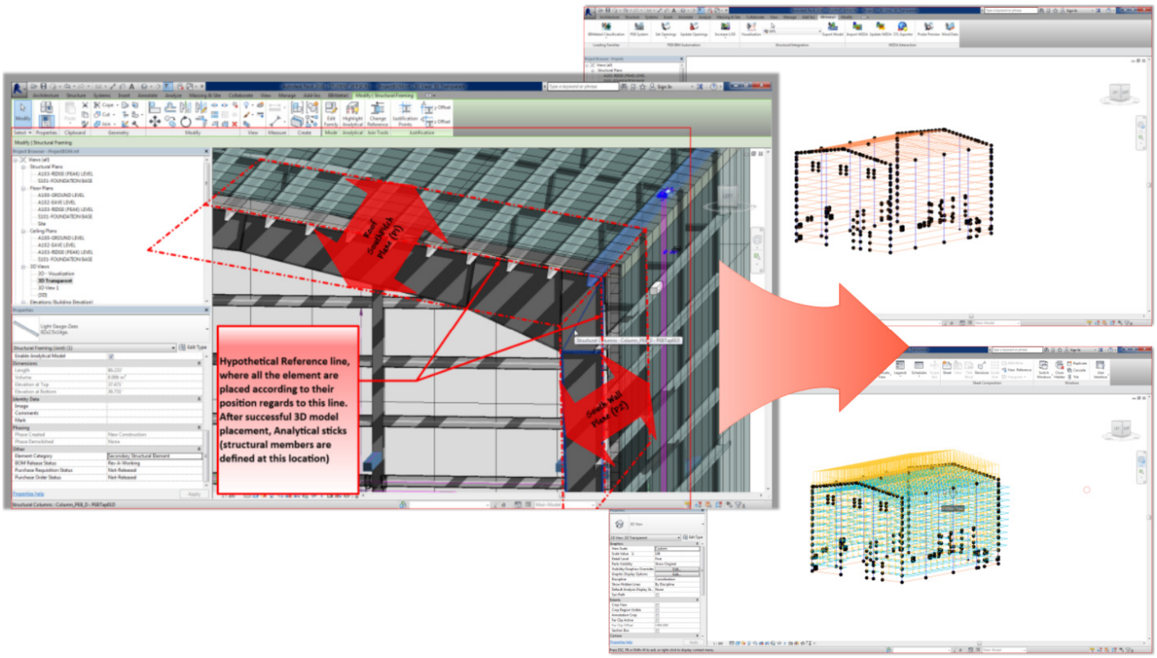


Fig. 3-14 Illustration of utilization of the planar concept in PEB framework for automating the process of structural model creation.

The analytical model and assigned loaded can be exported out (exchanged) with other structural design software for further analysis or assessment in combination with non-PEB components (Fig. 3-9). This research proposes some “load is transferring” extensions that could be a consideration for inclusion in the CIS/2 standard. Using an extended version of the CIS/2 standard, the entire model could be exchanged with other disciplines for specific structural connection developments and shop drawings in higher LODs.

As mentioned earlier the intent was to have the software support creating output models at a near optimal LOD (approximately 300, based on different classifications) ([12]-Chapter 1). At this LOD level, “models include elements in which Generic Components have been replaced with fully defined Assemblies. Analysis based on Specific Systems can be performed. Quantities based on Materials can be obtained[27]. However, a development process is still needed for increasing the LOD of the current model for further applications such as accurate interference studies, 2D detailing, accurate non-structural (tertiary elements such as flashings and capping) design, etc. These applications are commonly addressed in other construction sectors when using BIM processes and tools. Their application for the PEB sector would require an only incremental extension of the automation implemented so far.

As was briefly explained earlier, having the appropriate LOD models for the task at hand is very important and switching between levels is typically a laborious manual process (refer to Fig. 3-7). To address this, an adjustable or "Floating" LOD, supported by automated design tool capabilities, is proposed. Fig. 3-15 illustrates increment adjustment of the LOD through the PEB software for a selected wall element and the results in the details in the models. In other words, models of high-level systems elements, like walls, can be transformed into detailed models complete with all the constituent components necessary to build those systems (created in STEP 4 Fig. 3-12).

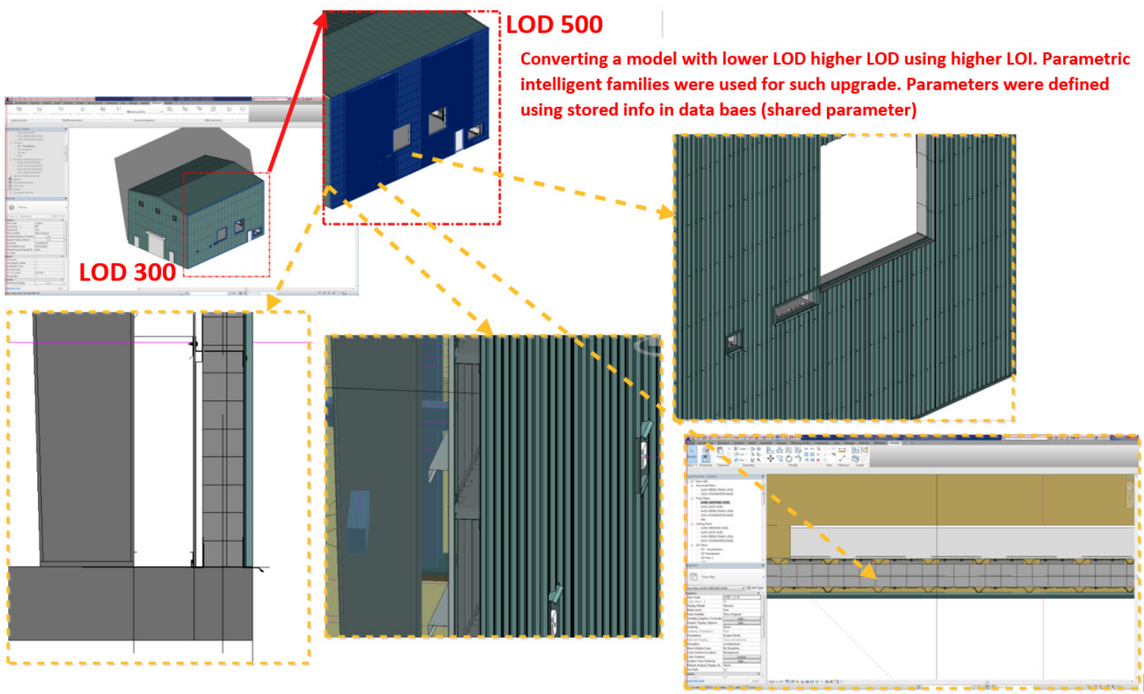


Fig. 3-15 Conversion process in "Floating LOD" concept. The selected Wall element is replaced by its constituent elements increasing the LOD of the model by using parametric modeling families and input information in step 4.

One of the main advantages and purposes of BIM is its support for data exchanges or communication between applications. True design collaboration cannot be performed without accurate and robust data exchange. The implemented PEB tool also ensures the developed PEB models can be exchanged with other applications, for example, the PEB model can be exchanged with CFD simulation software such as StarCCM+ for high-precision wind analysis. This capability was included in the developed PEB software to illustrate the benefits of automated 3D model creation for the building and the 3D boundary control volume. In this case, the PEB software uses the underlying functionality of the BIM software to convert the 3D model to a readable format (.STL) for CFD simulation software. Wind pressure monitoring points (probes) are defined, modeled and visualized by PEB software in the context of the designed building faces (again using planar concept). These points are added to BIM model for further result transfers and visualization (as back portal to receive the result of CFD analysis). The developed user input interface panel for CFD and Wind Engineering integration, created/visualized probes and the results of wind CFD analysis on the PEB BIM model inside the Revit environment are illustrated in Fig. 3-16.

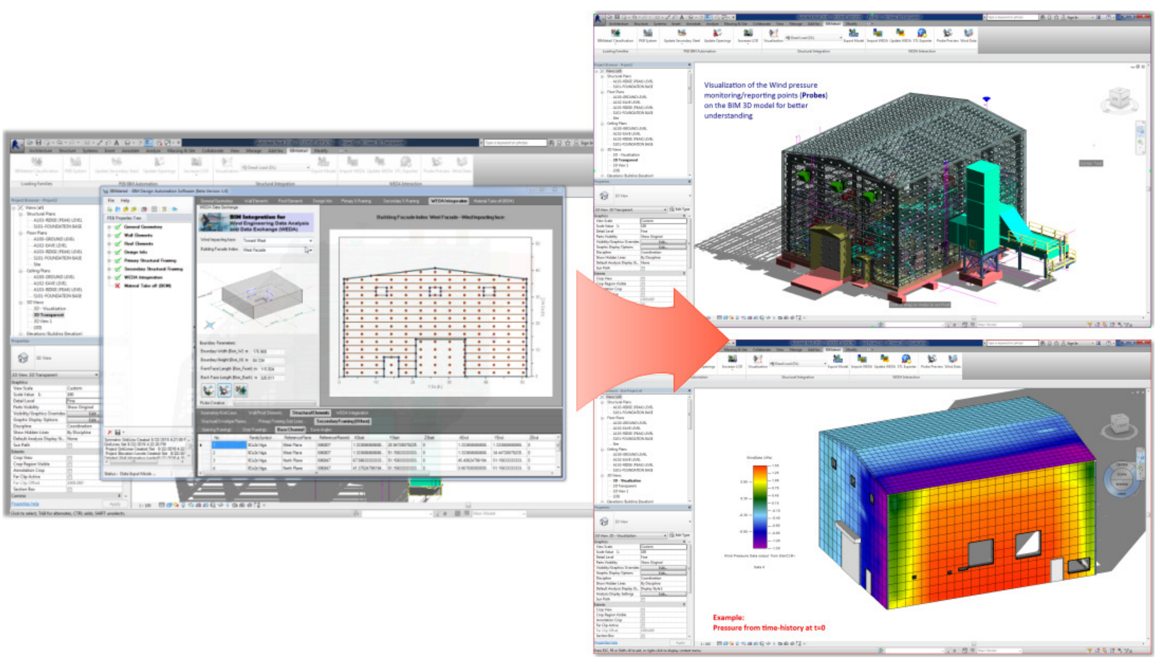


Fig. 3-16 Advanced Wind Engineering integration and built-in collaboration capability through proposed framework

One of the main selling points in the traditional approach for PEB industry is the capability for providing a full list of building materials (Bill of Material-BOM) for fabrication and installation. Any proposed BIM framework for PEB industry should be able to utilize BIM capabilities for material quantification. However, automated material quantification using BIM is still an ongoing and underdevelopment challenge. In summary, the main problem is that (in principle) BIM processes and tools are only capable of identifying and quantifying whatever exist in the model and database of the elements. 100 percent material take-off such as is being done in traditional PEB process, requires a new approach in BIM.

The approach taken by the authors is to use the floating LOD concept ability to capture the relationship between generic level elements, like walls, to their constituent components. However, some extra relationships beyond the components that can be easily be modeled in 3D need also are captured to deliver a complete materials breakdown (i.e. construction mortars or plastic vapor barriers). Typically, modeling these elements in 3D would not yield any value for the project. However, their quantities can be calculated using related modeled elements such as walls and roof elements. Eventually, materials not covered by the take-offs nor by calculation from related components can be quantified through a semi-automated/manual approach using BIM capabilities such as providing accurate snapping features (helper points). The developed tool gathers all this collected information of material quantification in a single Bill of Materials (BOM) database. The BOM can be shared with other project stakeholders, and disciplines such as the procurement department and project management team through a BIM-based (BIM database coordinated) system and stand-alone software platforms (as client-server portals for other stakeholders).

The whole explained system and procedures create a "comprehensive BIM coordinated procurement system" that manages the BOM and building materials data and automatically generates procurement documents such as Purchase Requisitions (PR) and Purchase Orders (PO) through ISO defined processes. Clearly this system can be considered as an added value to the existing traditional PEB material quantification and procurement system, while whole the process is done in BIM environment which has so many other collaborative applications as well. The API interface and some snapshot of the material database management process by the PEB BIM API are shown in Fig. 3-17.

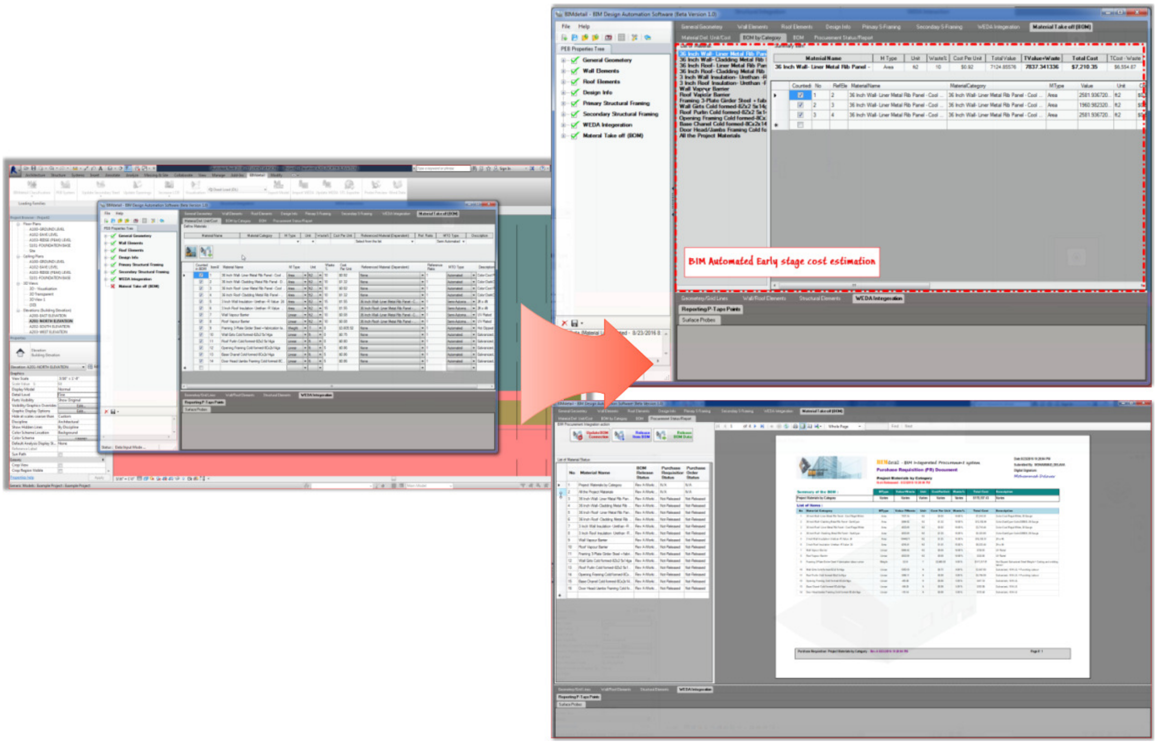


Fig. 3-17 Automated BIM-based material quantification and Bill of Material (BOM) and procurement document generation through proposed BIM framework

3.5.4 Results and discussion

The developed application effectively illustrates that a tool implementing the proposed BIM framework for PEB design can be built based on top of existing BIM technologies. It also demonstrates that it is possible to deliver both the automated design capabilities of the traditional PEB systems and the flexible and collaborative foundation of BIM.

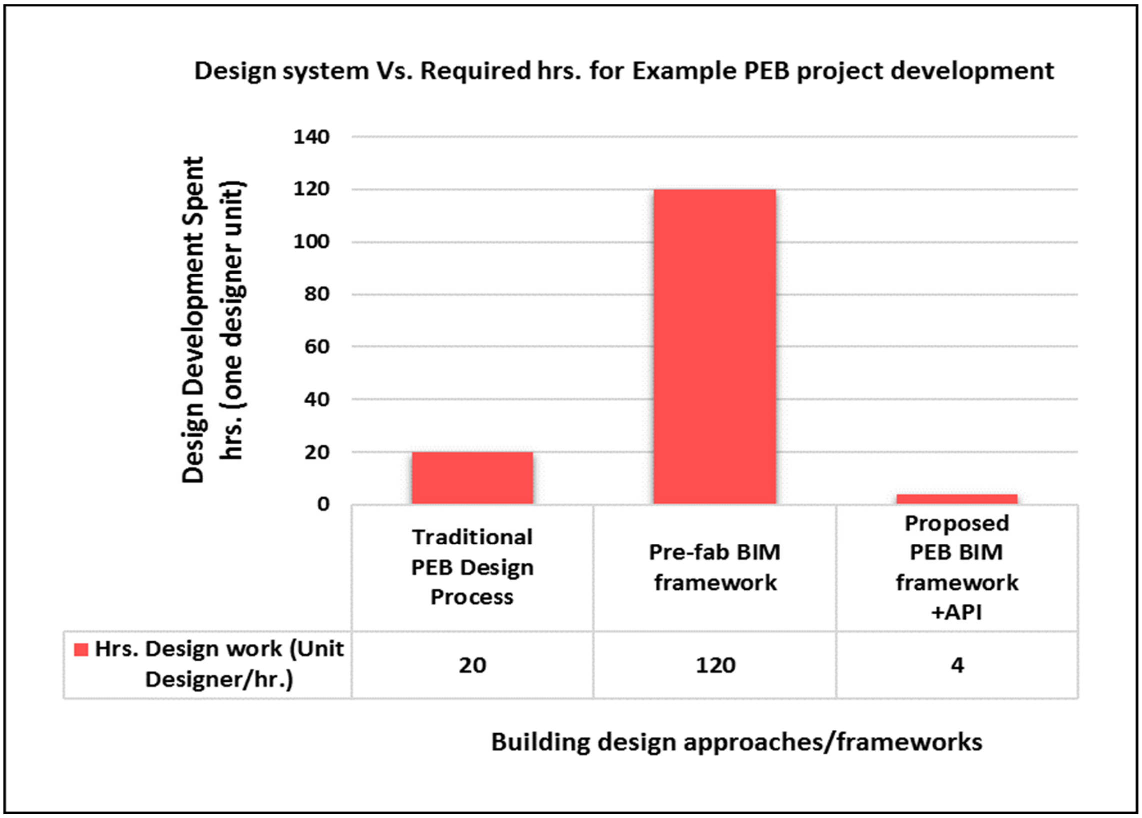


Fig. 3-18 Comparison of the performance of proposed PEB BIM framework Vs. traditional PEB approach and Pre-fab BIM framework

An approximation used for developing a performance-based comparison scheme between the proposed BIM framework, traditional PEB system and Pre-fab BIM framework for designing the example project. The results are shown in Fig. 3-18. The results indicate that using the proposed BIM framework can significantly reduce model and design development in comparison with the traditional Pre-fab BIM approach (illustrated in Fig. 3-18) due to the integrated design automation. Also in comparison, the proposed BIM framework uses a collaborative approach for modeling and locating the openings which save having to rely on manual CAD based trial and error (in the back and forth) approaches found in the traditional PEB system.

The authors' proposed approach also supports collaborative design activities based on BIM technologies and practices. Addressing the traditional PEB interoperability problem using the CSI/2 standard can allow the structural design information in the design model to be reused collaboratively. Hence the level of collaboration was improved using the proposed approach in comparison with existing BIM framework for general industry and Pre-fab.

One approach to evaluating the proposed framework is to see how it offers a resolution of existing issues with the design to operation process of the traditional PEB industry. M. Delavar et. al conducted research on a case study PEB project (an industrial sensitive and collaborative project) to identify issues occurred in the absence of BIM implementation ([12]-Chapter 1).

Table 3-1 shows the results of the case study PEB project. This case study analyzed all documented project issues such as rework, repairs and reorders to classify and categorize all the issues in five sections ([12]-Chapter 1). All the results based on the relative percentage per category is presented in Table 3-1. To address such comparison base discussion, the probable resolutions offered by the BIM implementation (using the proposed framework) for covering those issues are presented for each category in Table 3-1 as well. As it is discussed and explained in Table 3-1, the proposed BIM framework demonstrably improves the design and construction of PEB buildings.

Table 3-1 Probable improvements and resolutions offered by the proposed BIM framework for PEB industry presented on the result of the case-study ([12]-Chapter 1).

No	Project Issues (NCRs, Reworks, repairs, reorders, etc.)	Percentage (%)	Resolution by proposed BIM framework
1	Clashes and 3D Coordination	**29.70%**	Resolution by creating a collaborative BIM 3D design environment to predict and eliminate any probable clashes and interference by utilizing other disciplines BIM model in the design process of PEB buildings
2	None-Structural Element Reworks	**28.90%**	Using "Floating LOD" concept accurate designing process for the nonstructural elements such as light-gauge metal flashing and sealing elements is possible by utilizing a high LOD model. 2D detailing views can be created temporarily for shop-drawing purposes.
3	Inaccuracy in Procurement Documentation	**18.74%**	Confusion and Inaccuracies in creation and management of the procurement documents can be improved by proposed BIM coordinated procurement system
4	Structural Element Reworks	**15.44%**	Collaborative BIM 3D environment could eliminate any required reworks regarding structural elements clashes.
5	Inaccuracy in BOM	**7.49%**	As described the proposed comprehensive BIM-based automated material quantification system which uses a combination of couple automated and semi-automated approaches can increase the accuracy of material quantifications and BOM generations.

Finally, it is suggested that some of the main problems occurred during the design and construction of the example project (accomplished using traditional PEB system) could be eliminated by using the proposed BIM framework and project could meet its milestones and time-frame easier. Also, the owner could achieve a high LOD BIM model as an ultimate asset for facility and operation management.

3.6 Conclusion

The "Design to Operation" system of PEB industry and efforts for developing a comprehensive BIM framework for PEB industry were presented in this paper. The processes of BIM implementation and its framework for the Pre-fab industry as a similar industry to PEB industry were illustrated and discussed. New BIM processes, project collaboration workflows/process maps and data-exchange strategies were developed and put into a proposed BIM framework for PEB industry and illustrated in this paper. An example PEB project was followed through the proposed workflow illustrating its value.

The main technical challenges in developing a BIM framework for PEB industry were identified to be, preserving design automation while allowing for design customization within a BIM system, shifting between LOD levels to support design and achieving interoperability with other tools. In particular, a "Planar Concept" and "Floating LOD" approach were developed to address issues preventing the use of automation in the PEB design development.

The software was developed and evaluated for feasibility approach and algorithms proposed by the BIM framework. The results indicated a significant improvement in the project collaboration quality and design development time consumption and cost. In particular, the approach used here easily supports a far more comprehensive BIM coordinated procurement system which could eliminate many of the costly inaccuracies in BOM and procurement documents.

Finally, the authors propose that the BIM frameworks and associated concepts developed here can improve the collaboration between different disciplines in the design of a PEB projects by simplifying or enabling model and analysis information exchange.

Acknowledgement

Natural Science and Engineering Research Council of Canada (NSERC) is gratefully acknowledged for the financial support to conduct this research project. The authors also wish to thank ATCO Emissions Management (ATCOEM) as a former sponsoring company. Last but not the least; the authors would like to show their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was developed.

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Chapter 4

4 BIM Optimal Level of Development (LOD)

Abstract

The selection and application of an appropriate Level of Development (LOD) is one of the main challenges during the adaption and implementation of Building Information Modeling (BIM) processes. Project appropriate LOD selection for models needs to encompass most, if not all, of the information requirements of a project's goals while avoiding imposing unnecessary modeling time and costs from over specification. The goal of this work is to identify what the optimum or ideal LOD should be based on common industry project applications of BIM and their associated costs and benefits. The proposed LOD optimum is found using a mathematical approach based on industry assessments of the advantages and Return on Investment (ROI) data collected in recent respected international BIM surveys for different BIM uses.

A Pre-Engineered Building (PEB) project example is used to show that LOD300 models can realize with reasonable effort and those models can support the desired uses, like coordination, estimation, and clash detection.

Keywords:

Level of Development (LOD), Level of Details, Level of Information (LOI), Optimum LOD concept, Building Information Modeling (BIM), Return on investment (ROI) of BIM, Frequency and benefits of BIM uses, Pre-Engineered Buildings (PEB)

4.1 Introduction

Although there is a high level of growth in BIM implementation in the construction industry, interoperability and BIM level of development (LOD) challenges still remain. Identifying an appropriate level of model development to meet specific project requirements and then developing BIM models to that level have been identified as essential challenges to overcome[1].

The Level of Development (LOD) Specification is a reference that enables practitioners in the AEC Industry to specify and articulate; with a high level of clarity, the content and reliability of Building Information Models (BIMs) at various stages in the design and construction process[2]. Some of the earlier uses of BIM LOD were those used by Vico Software. They pioneered work beginning in 2004 on a Model Progression Specification (MPS) for the BIM industry. The core of the MPS is the "Level of Details" definitions/descriptions of the steps through which a BIM element can logically progress from the lowest level of conceptual approximation to the highest level of representational precision. The five levels were Conceptual (100), Approximate geometry (200), Precise geometry (300), Fabrication (400), and As-built (500). LOD identifies how much information is known about a model element at a given time[3,4]. Another example includes the first set of Level of Development definitions in AIA Document E202™-2008 Building Information Modeling Protocol.

LOD research questions, in general, can be categorized into two: "how much a BIM model is required to be developed for specific uses in a project?" and "how to develop a model to that level efficiently?". In this paper (i) a brief review of most commonly utilized LOD specifications are presented and then compared; (ii) a mathematical approach for finding a hypothetical optimal LOD to be considered for generalized application cases is discussed; and (iii) its application in the Pre-Engineered Building (PEB) domain is demonstrated in a mostly automated PEB design system.

4.2 Review of LOD Classifications

Some of the most commonly utilized LOD Classifications include those developed by (i) American Institute of Architects (AIA), (ii) AEC (UK) BIM Protocol, Construction

Industry Council (CIC) – Publicly Available Specification (PAS) 1192-2, (iii) US Army Corps of Engineers (USACE) Minimum Modeling Matrix (M3), (iv) BIMForum, and (v) National Australian NATSPEC National BIM Guide. Although there are many more country-specific classifications, such as the Chinese CIC LOD specification and the Danish LOD classification, the classifications selected here are broadly adopted both in North America and internationally and are generally representative.

4.2.1 American Institute of Architects (AIA)

In 2008, the AIA published its first set of Level of Development definitions in its AIA Document E202™-2008 Building Information Modeling Protocol (e.g. Table **4-1**). The AIA California Council IPD Committee and the AIA Contract Documents Committee adopted the LOD concept as the core of its E202™-2008 Building Information Modeling Protocol (AIA 2008). AIA-G202-2013 comprehensively describes LODs and Table **4-2** is only a summarized adaption of it. The difference between Table **4-1** and Table **4-2**, shows how the LOD standard has evolved from 2008 to 2013.

Table 4-1 - Model Progression specifications (AIA) AIA-E202-2008.[a] [5]

Level of detail	**100**	**200**	**300**	**400**	**500**
Model content	**Conceptual**	**Approximate geometry**	**Precise geometry**	**Fabrication**	**As-built**
Design & Coordination (function/from/behavior)	Non-geometric data or line work, areas, volumes, zones etc.	Generic elements shown in three dimensions • Maximum size • Purpose	Specific elements Confirmed 3D Object geometry • dimension • capacities • connections	Shop drawing/fabrication • purchase • manufacture • Install • specified	As-built • actual

[a] A portion of table adapted from American Institute of Architects, AIA-E202-2008 element model table.

Table 4-2 - LOD Specifications adopted from AIA-G202-2013[6]

Level of Development (LOD)	Description
100 **Conceptual**	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, the tonnage of HVAC, etc.) can be derived from other Model Elements. **Approved uses:** Analysis, cost estimating and scheduling
200 **Generic Placeholders**	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. **Approved uses:** Analysis, cost estimating and scheduling
300 **Specific Assemblies**	The Model Element is graphically represented within the Model as a specific system, object or assembly accurate in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. **Approved uses:** Construction, analysis, cost estimating and scheduling
400 **Detailed Assemblies**	The Model Element is graphically represented within the Model as a specific system, object or assembly that is accurate in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element **Approved uses:** Construction, analysis, cost estimating and scheduling
500 **As built**	The Model Element is a field-verified representation in terms of size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements

4.2.2 AEC (UK) BIM Protocol – Level of Details (LOD)

The AEC (UK) Initiative was formed in 2000 to improve the process of design information production, management and exchange. Initially, the initiative addressed CAD layering conventions as the primary concern for users of design data. As design needs and technology developed, the initiative expanded to cover other aspects of design data production and information exchange. The committee was re-formed in 2009 to address the growing need within the UK AEC industry for application of UK standards in a unified, practical and pragmatic manner within a design environment. The AEC (UK) BIM Protocol was first released in November 2009, and this updated version integrates the learning and experience gained since then. This generic document provides platform-independent protocols which are further enhanced by the software- specific supplements[7]. AEC (UK) BIM Protocols (2012) defines graphical and non-graphical attributes separately. Coding for graphical representations, the Level of Detail (LOD), is easy enough. Table **4-3** presents what the AEC (UK) BIM Protocols [7] defines as the graphical appearance.

Table 4-3 - Level of Detail description AEC (UL) BIM Protocol V2 - Under Field7/Grades[7]

LOD	Description
G0	Symbolic (not representative of the physical object) This might be used for electrical symbols or an object which is modeled the same regardless of scale
G1	Low resolution conceptual placeholder (e.g. 1:500, 1:200)
G2	Medium resolution detailed component for design/construction (e.g. 1:100, 1:50 max)
G3	High resolution, fully detailed object. Typically, only used for visualization.

AEC (UL) BIM Protocol V2 includes suggests appends LOD granularity to library objects as a clarifying naming convention. Table 4-4 contains examples of this naming convention for elements in an object library including the level of granularity.

Table 4-4 - Example of LOD application and description AEC (UL) BIM Protocol V2[7]

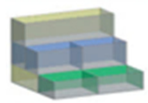
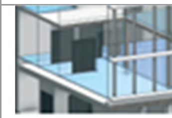
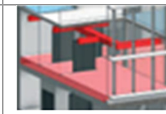
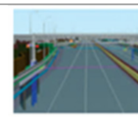
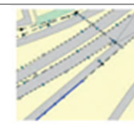
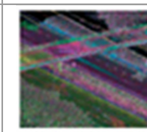
Object File Name	Description
G25-WallBrick-102.5-M3-G2	Brick wall, 102.5mm wide, 3-dimensional, grade suitable for up to 1:50 models (e.g. no brick bond defined or wall ties)
DoorInternal-M3-G1	Generic internal door, not specifically sized, 3-dimensional, grade for schematic modeling purposes of ~1:200. Classification included as a property of the object.
G322-DoorInternal-826-P-G2	Internal door of 826mm wide, intended for plan use at up to 1:50 scale.
Premdor-63990-838x1981x35-M3-G3	Internal door made by "Primdor", model reference 63990 (838 x 1981 x 35mm), 3-dimensional, fully detailed with ironmongery. Classification included as a property of the object.
S-G2613-B01-Westok-1160x267x134CUB-M3-G2	Structural owned steel beam, described as a "B01" (structural engineering naming for a beam type 1), made by "Westok", with a section size of 1160 x 267 x 134 CUB, 3-dimensional, grade suitable for 1:50 models.
E-G6432-PowerOutlet-P-G0	Electrical symbol representing a plug socket, intended for plan use.

4.2.3 Construction Industry Council (CIC) - PAS 1192-2

Publicly Available Specifications (PAS) 1192-2:2013, which came into effect on 28 February 2013, is a specification for information management for the capital/delivery phase of construction projects using building information modeling. It is sponsored by the Construction Industry Council (CIC) and published by The British Standards Institution. CIC commissioned it as part of its response to the UK Government Construction Strategy which stated that the government requires fully collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum by 2016. This request represents a requirement for Level 2 BIM on centrally procured public projects. Level 2 is a managed 3D environment with data attached but created in separate discipline models. PAS 1192-2 specifies the requirements for achieving building information modeling (BIM) Level 2 during the capital/delivery phase of projects. It builds on the existing code of practice for the collaborative production of architectural, engineering and construction information, defined by BS 1192:2007 and it is one of a number of standards, protocols and tools available to support the adoption of Level 2 BIM in the UK construction industry[8].

PAS 1192-2 defines two components for LOD, namely the "level of definition" (Levels of model detail (LOD), that relates to the graphical and geometrical content of models), and the Levels of model information (LOI) that relates to the non-geometric content of models. In fact, the two are closely aligned, as it is normal for geometric and non-geometric content to develop alongside one another. The levels of model detail and model information are defined for key stages of the project, at which "data drops" (information exchanges) take place, allowing the user to verify that project information is consistent with their requirements and enabling them to decide whether to proceed to the next stage. This definition is analogous to a stage report on a conventional project[8]. As it was mentioned, LOD in PAS 1192-2 is a classification which describes a model regarding the status of existing information and graphical development at the same time. An illustration from PAS 1192-2 is presented in Table 4-5.

Table 4-5 - Part of the Levels of Definition table from PAS 1192-2. © 2013[9]

Stage number **Model name**	**1** **Brief**	**2** **Concept**	**3** **Definition**	**4** **Design**	**5** **Build and Commission**	**6** **Handover and Closeout**	**7** **Operation**
Systems to be covered	N/A	All	All	All	All	All	All
Graphical illustration (building project)							
Graphical illustration (infrastructure project)							
What the model can be relied upon for	Model information communicating the brief, performance requirement, performance benchmarks, and site constraints	Models which communicate the initial response to the brief, aesthetic intent and outline performance requirement. The model can be used for early design development, analysis, and coordination. Model content is not fixed and may be subject to further design development. The model can be used for coordination, sequencing and estimating purposes	A dimensionally correct and coordinated model which communicates the response to the brief, aesthetic intent and some performance information that can be used for analysis, design development, and early contractor engagement. The model can be used for coordination, sequencing and estimating purposes including the agreement of a first stage target price	A dimensionally correct and coordinated model which communicates the response to the brief, aesthetic intent and some performance information that can be used for analysis, design development, and early contractor engagement. The model can be used for coordination, sequencing and estimating purposes including the agreement of a first stage target price/ guaranteed maximum price	An accurate model of the asset before and during construction incorporating coordinated specialist sub-contract design models and associated model attributes. The model can be used for sequencing of installation and capture of as-installed information	An accurate record of the asset as a constructed at handover, including all information required for operation and maintenance	An updated record of the asset at a fixed point in time incorporating any major changes made since handover, including performance and condition data and all information required for operation and maintenance The full content will be available in the yet to be published PAS 1192-3

4.2.4 US Army Corps of Engineers (USACE) Minimum Modeling Matrix (M3) LOD-Grade

The US Army Corps of Engineers has released their Minimum Modeling Matrix or "M3". This document is a spreadsheet that contains three worksheets: Instructions, Modeling Requirements, and Scope-LOD-Grade. The USACE M3 document utilizes the AIA LOD definitions and classifies the built environment with a minimum level of required information from design and construction teams. USACE M3 categorizes the built environment and then includes references to Omniclass, Uniformat, and MasterFormat (Fig. 4-1). Fig. 4-1 shows that this classification implementation even allows the user to filter the Scope-LOD-Grade worksheet in column A to show a different level of specificity (as in Uniformat, Level 1, 2, 3 and 4) [9,10]. The integrated LOD Table in the USACE M3 document is shown in Table 4-6.

Table 4-6 – (Table 2.1 of USACE M3) LEVEL OF DEVELOPMENT DEFINITIONS (ACCURACY) [9]

LOD	Definition
●	Refer to the specific child element for appropriate LOD. (Used for categories that have multiple sub-elements for which varying LOD apply.)
100	Model Elements indicative of area, height, volume, location, and orientation may be modeled geometrically or represented by other data (i.e., a pump would be a cube.)
200	Model Elements are modeled as generalized systems or assemblies with approximate quantities, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements (i.e., a pump would be a generic pump of approximate size.)
300	Model Elements are modeled as specific assemblies accurate in terms of quantity, size, shape, location, and orientation. Non-geometric information may also be attached to Model Elements. Accurate to the degree dimensioned or indicated on contract documents (i.e., a pump would be a generic pump of accurate size complete with connections and clearances for a complete system.)

The USACE (M3) also includes another classification that defines the grades of LOD. Within each Level of Development, there is the potential to represent information in various formats. In practice, it has been proven that there are certain elements for which there is a greater benefit in providing 3-dimensional representation, while in others drafting or representation in the form of narratives is sufficient for a particular deliverable [9]. Table 4-7 presents the LOD grading used by USACE M3.

Table 4-7 – (Table 2.2 of USACE M3) ELEMENT GRADE DEFINITIONS (FORMAT) [9].

Grade	Description
A	3D + Facility Data
B	2D + Facility Data
C	2D Only (Drafting, linework, text, and or part of an assembly)
+	Original Grade (A, B, or C) adjusted for contract changes and field conditions.
-	Not included in or tied to the model (however is still required in the deliverable)
●	Refer to the specific child element for appropriate Grade. (Used for categories that have multiple sub-elements for which varying Grades apply.)

As it is illustrated in Fig. 4-1, USACE_M3 spreadsheets classify different modeled components of a building (Model Element Table) regarding the status of the BIM model used for “Design” and “As Built” purposes. In other words, this classification grades a model’s utility for design and/or as an as-built record model, two main BIM applications.

Minimum Modeling Matrix (M3)
Version: 1.3 (SEPT-19-2014)

							DESIGN MODEL (CONSTRUCTION DOCUMENTS)	RECORD MODEL (AS-BUILTS)	FOR AGENCY OR CONTRACTOR INTERNAL USE. NOT A CONTRACTUAL REQUIREMENT.	
Level	Element ID	OmniClass ID	UniFormat ID	MasterFormat ID	Included in Facility or Site? (change to NO if NOT part of project scope)	LOD	GRADE (CD)	GRADE (AB)	Primary Discipline (This will allow the team to identify discipline-specific areas of content)	Notes
Level 1	SUBSTRUCTURE	21-01 00 00	A		Yes	•	•	•	Structural	
Level 2	FOUNDATIONS	21-01 10	A10		Yes	•	•	•	Structural	
Level 3	Standard Foundations	21-01 10	A1010		Yes	•	•	•	Structural	
Level 4	Wall Foundations	21-01 10 10	A1010.10		Yes	300	A	A+	Structural	
Level 4	Column Foundations	21-01 10 10 10	A1010.30		Yes	300	A	A+	Structural	
Level 4	Standard Foundation Supplementary Components	21-01 10 10 30	A1010.90		Yes	200	C	C+	Structural	
Level 3	Special Foundations	21-01 10 20	A1020	31 60 00	Yes	•	•	•	Structural	
Level 4	Driven Piles	21-01 10 20 10	A1020.10	31 62 00	Yes	300	A	A+	Structural	
Level 4	Bored Piles	21-01 10 20 15	A1020.15	31 63 00	Yes	300	A	A+	Structural	
Level 4	Caissons	21-01 10 20 20	A1020.20	31 64 00	Yes	300	A	A+	Structural	
Level 4	Special Foundation Walls	21-01 10 20 30	A1020.30	31 66 16	Yes	300	A	A+	Structural	
Level 4	Foundation Anchors	21-01 10 20 40	A1020.40	31 68 00	Yes	100	C	C+	Structural	
Level 4	Underpinning	21-01 10 20 50	A1020.50	31 48 00	Yes	100	C	C+	Structural	
Level 4	Raft Foundations	21-01 10 20 60	A1020.60	03 71 00	Yes	300	A	A+	Structural	
Level 4	Pile Caps	21-01 10 20 70	A1020.70		Yes	300	A	A+	Structural	
Level 4	Grade Beams	21-01 10 20 80	A1020.80		Yes	300	A	A+	Structural	
Level 2	SUBGRADE ENCLOSURES	21-01 20	A20		Yes	•	•	•	*Architectural, Structural*	
Level 3	Walls for Subgrade Enclosures	21-01 20 10	A2010		Yes	•	•	•	*Architectural, Structural*	
Level 4	Subgrade Enclosure Wall Construction	21-01 20 10 10	A2010.10		Yes	300	A	A+	*Architectural, Structural*	

Fig. 4-1 Scope-LOD-Grade worksheet - USACE (M3)

4.2.5 BIMForum LOD Classification

The BIMForum is operating as a unified group whose mission is: "to facilitate and accelerate the adoption of building information modeling (BIM) in the AEC industry." [2] The group is closely connected with the Associated General Contractors (AGC) of America and collaborates with industry organizations such as American Institute of Architects, National Institute of Building Sciences, National Institute of Standards and Technology, International Alliance for Interoperability, Collaboration Techniques Tools and Technologies (C3T) Task Force of AGC of America, the 3xPT Strategy Group, formed by the Construction Users Roundtable (CURT®)[2]. The group has established several sub-groups to address each relevant industry sector and topic[11].

To help further the standardization and consistent use of the LOD concept, and to increase its usefulness as a foundation for collaboration, the AIA agreed to allow the BIMForum organization to use its latest LOD definitions in this Specification in early 2011. A LOD Working Group was formed under the auspices of the BIMForum and began developing the LOD framework into a consensus-based document. The LOD definitions that are used in this document are identical to those to be published in the AIA's updated Digital Practice Documents, with two exceptions[3].

First, the working group identified the need for a LOD; that defined model elements sufficiently, developed to facilitate coordination between disciplines, e.g., clash detection/avoidance, layout, etc. The requirements for this level are higher than those for 300, but not as high as those for 400. Thus it was designated LOD 350. The original AIA documents do not include LOD 350, but the 2013 document releases and associated Guide and Instructions references it. Second, while LOD 500 is included in the AIA's LOD definitions, the working group did not feel it was necessary to define further and illustrate LOD 500 in this specification as it relates to field verification. Accordingly, the expanded descriptions and graphical illustrations in this Specification are limited to LOD 100-400[12].

The first draft of the resulting Level of Development Specification was released for public comment at the Miami BIMForum in April 2013 [2]. Table **4-8** contains the AIA and BIMForum LOD classification interpretations.

Table 4-8 - BIMForum LOD Classification - Fundamental LOD Definitions Sec. 2.3) – Edition 2016

Level of Development (LOD)	**Description**
100	The Model Element may be graphically represented in the Model with a symbol or other generic representation, but does not satisfy the requirements for LOD 200. Information related to the Model Element (i.e. cost per square foot, tonnage of HVAC, etc.) can be derived from other Model Elements. **BIMForum Interpretation:** LOD 100 elements are not geometric representations. Examples are information attached to other model elements or symbols showing the existence of a component but not its shape, size, or precise location. Any information derived from LOD 100 elements must be considered approximate.
200	The Model Element is graphically represented within the Model as a generic system, object, or assembly with approximate quantities, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. **BIMForum interpretation:** At this LOD elements are generic placeholders. They may be recognizable as the components they represent, or they may be volumes for space reservation. Any information derived from LOD 200 elements must be considered approximate.
300	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of quantity, size, shape, location, and orientation. Non-graphic information may also be attached to the Model Element. **BIMForum interpretation:** The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.

350	The Model Element is graphically represented within the Model as a specific system, object, or assembly in terms of quantity, size, shape, location, orientation, and interfaces with other building systems. Non-graphic information may also be attached to the Model Element. **BIMForum interpretation:** Parts necessary for coordination of the element with nearby or attached elements are modeled. These parts will include such items as supports and connections. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
400	The Model Element is graphically represented within the Model as a specific system, object or assembly in terms of size, shape, location, quantity, and orientation with detailing, fabrication, assembly, and installation information. Non-graphic information may also be attached to the Model Element. **BIMForum interpretation:** A LOD 400 element is modeled at sufficient detail and accuracy for fabrication of the represented component. The quantity, size, shape, location, and orientation of the element as designed can be measured directly from the model without referring to non-modeled information such as notes or dimension call-outs.
500	The Model Element is a field verified representation regarding size, shape, location, quantity, and orientation. Non-graphic information may also be attached to the Model Elements. **BIMForum interpretation:** Since LOD 500 relates to field verification and is not an indication of progression of a higher level of model element geometry or non-graphic information, this Specification does not define or illustrate it.

One of the main advantages of BIMForum LOD classification is the “suggested” [12] 3D illustration for each building component in the model element table. These 3D representations are linked to other information in model element table such as OmniClass reference#[13] and UniFormat reference#[14]. This feature of the BIMForum LOD classification significantly helps BIM users to comprehend the contrast between different levels. Fig. 4-2 provides an example of the BIMForum LOD specification. BIMForum makes a substantial effort to update its classification and 3D illustration annually.

Level of Development
Specification
Version: 2015

www.bimforum.org/lod

B1010.10 – Floor Structural Frame (Steel Framing Bracing Rods)

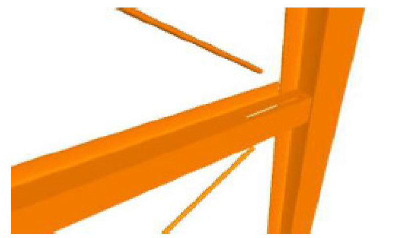
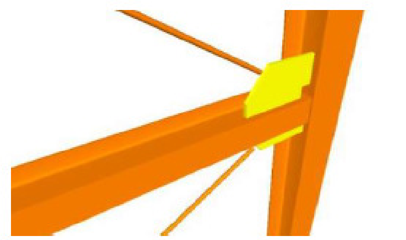
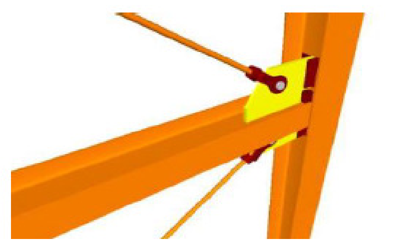
100	See B10	
200	See B1010	
300	Element modeling to include: • Specific sizes of main structural braces modeled per defined structural grid Required non-graphic information associated with model elements includes: • Structural steel materials	 *27 B1010.100-LOD-300 Floor Structural Frame (Steel Framing Bracing Rods)*
350	Element modeling to include: • Connection details • Actual elevations and location of member connections • Large elements of typical connections applied to all structural steel connections such as base plates, gusset plates, anchor rods, etc. • Any miscellaneous steel members with correct orientation	 *28 B1010.100-LOD-350 Floor Structural Frame (Steel Framing Bracing Rods)*
400	Element modeling to include: • Welds • Clevis • Bolts, washers, nuts, etc. • All assembly elements	 *29 B1010.100-LOD-400 Floor Structural Frame (Steel Framing Bracing Rods)*

Fig. 4-2 - An example of BIMForum LOD specification 3D illustration on Model Elements Table [15]

4.2.6 National Australian NATSPEC BIM Guide (US VA BIM Guide)

The NATSPEC National BIM Guide is an adopted version of the US Department of Veteran Affairs (VA) [16] BIM Guide[17]. The NATSPEC recommends the use of the BIMForum LOD Specification for model graphic information and “NATSPEC BIM object element matrix” for Model non-graphic information [4]. Fig. 4-3 illustrates this definition of NATSPEC for a complete LOD classification.

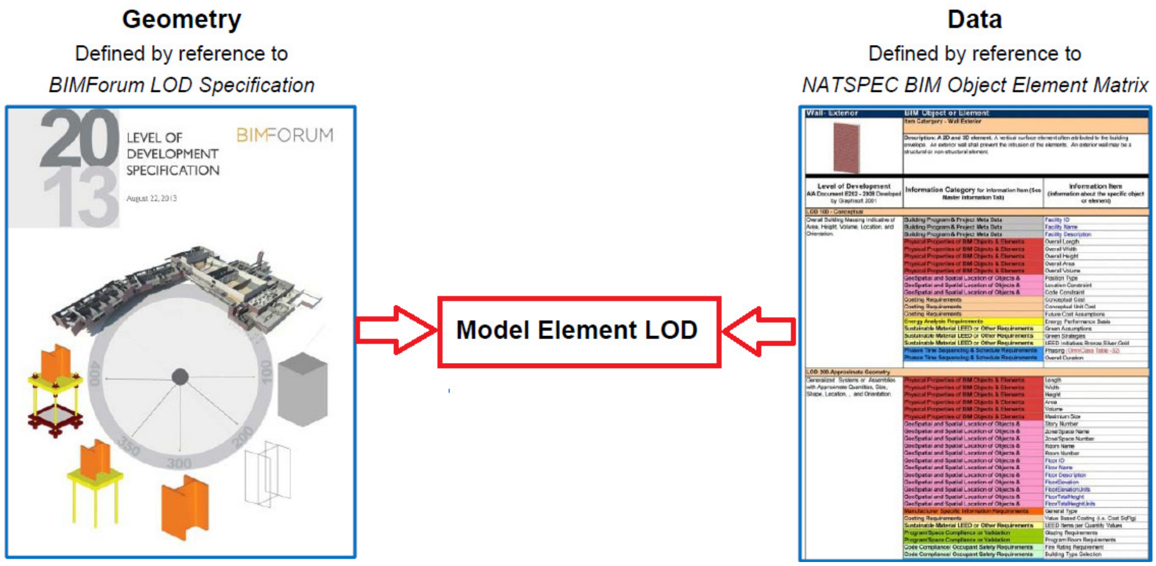


Fig. 4-3 - NATSPEC LOD Classification Reference[4]

Hence, NATSPEC does not suggest or propose new granularity instruction for LOD classification. NATSPEC "BIM and LOD" guide rearrange the AIA-G202-2013 LOD table (Table 4-8) as can be seen in Table 4-9.

Table 4-9 – Re-arranged AIA-G202-2013 LOD classification per application[4,6]

	LOD 100 **Conceptual**	**LOD 200** **Approx. geometry** **Performance**	**LOD 300** **Precise geometry** **Performance**	**LOD 400 Fabrication**	**LOD 500** **As-built**
Analysis	Analysis based on volume, area and orientation by application of **generalized** performance criteria assigned to **other** Model Elements.	Performance analysis of selected systems by application of **generalized** performance criteria assigned to the **representative** Model Elements.	Performance analysis of selected systems by application of **specific** performance criteria assigned to the **representative** Model Element.	Performance analysis of systems by application of **actual** performance criteria assigned to the Model Element.	Performance measured from installed systems.
Cost Estimating Development	Development of a cost estimate based on **current** area, volume or similar **conceptual** estimating techniques (e.g., square metres of floor area, hospital bed, etc.).	Development of cost estimates based on **approximate** data provided and **quantitative** estimating techniques (e.g., volume and quantity of elements or type of system selected).	Development of cost estimates suitable for procurement based on the **specific** data provided.	Costs are based on the **actual** cost of the Model Element at buyout.	Operation and maintenance costs measured from installed systems.
Project scheduling	Project phasing and determination of **overall** Project duration.	For showing ordered, time-scaled appearance of **major** elements and systems.	For showing ordered, time-scaled appearance of **detailed** elements and systems.	For showing ordered, time-scaled appearance of **detailed specific** elements and systems **including construction means and methods**.	Maintenance scheduling derived from installed systems.
Project Coordination	N/A	**General** coordination with other Model Elements in terms of its size, location and clearance to other Model Elements.	**Specific** coordination with other Model Elements in terms of its size, location and clearance to other Model Elements including **general** operation issues.	Coordination with other Model Elements in terms of its size, location and clearance to other Model Elements including **fabrication**, **installation** and **detailed** operation issues.	N/A

Other authorised uses Additional	Additional Authorised Uses of the Model Element developed to **LOD 100**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of AIA E203- 2012.	Additional Authorised Uses of the Model Element developed to **LOD 200**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of AIA E203- 2012.	Additional Authorised Uses of the Model Element developed to **LOD 300**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of AIA E203- 2012.	Additional Authorised Uses of the Model Element developed to **LOD 400**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of AIA E203- 2012.	Specific Authorized Uses of the Model Element developed to **LOD 500**, if any, including Authorized Uses identified or required by the uses set forth in Section 4.4 of AIA E203- 2012.

4.2.7 LOD classifications, contrasts and discussion

Performing any direct comparison between different introduced LODs may not be feasible regarding the differing nature and motivations for the development of them. In summary, the AIA in 2008 brought a clear model level specification and schema together and related it to a table of elements to be modelled. The AIA incorporated all their predecessors' efforts and kept developing the LOD classification up until their 2013 version. Most of the other introduced specifications and guides such as BIMForum, NATSPEC and USACE have subsequently been built and developed based on the work of the AIA. Other mentioned classifications have tried to bring more clarity to AIA by adding 3D illustrations or by linking it to other (application based, referred to USACE and NATSPEC) model element tables. These 3D illustrations and links enhance the clarity and thus feasibility of implementing the LOD classification in BIM execution plans and the utility of BIM on a daily basis. These efforts have also somewhat extended the established AIA LOD classification beyond its original architectural based perspective[18].

BIM organizations in UK have tried to develop LOD classifications as an asset for better implementation of BIM that is in line with its mandatory level 2 BIM implementation. The AEC UK protocol and BSI PAS 1192-2 try to present LOD as a 3D graphic and information management tool. This protocol has provided support for the separation of 3D representations and non-geometrical information. Based on their approach, UK standards define Level of Detail with comprehensive instructions for the management of Level of Information (LOI) [7,8].

4.2.8 Level of Development vs. Level of Detail

According to the AIA release document, E202 LOD is an acronym for Level of Development[5]. The confusion comes from the fact that the acronym LOD was originally used by "Vico" software to stand for Level of Detail[4] (and likewise also commonly used by the computer graphics software for Level of Detail). The initial purpose of LOD definition by "Vico" was to develop a tool for automating BIM material quantification and later on for application of BIM for construction management (4D and 5D modeling) [19]. AIA adopted the LOD acronym, but changed its meaning to "Level of Development" instead of “Level of Detail.” The justification for the similar acronyms with conflicting meanings is that the word “detail” referred to graphical detail while “development” referred to the level of certainty about an object on mode.

BIMForum suggests that Level of Detail is essentially how much detail is included in the model element. Level of Development is the degree to which the element’s geometry and attached information have been thought through – the degree to which project team members may rely on the information when using the model. [12]

4.2.9 Level of Development (LOD) vs. Level of Information (LOI)

As it was indicated earlier, the difference between LOD and LOI needs to be tracked more on the classifications and guidelines developed in the UK. Even PAS 1192-2 clearly defines that LOD (as Level of Definition) = Level of Information + Level of Details[8].

A building information model contains both graphical and non-graphical information, accurately linked and clearly structured. As stages progress and proposals develop, the graphical and non-graphical data build in a shared digital space, known as a Common Data Environment (CDE). CDE is a user-friendly collaborative environment which uses guidance given under PAS1192 and BS1192, to coordinate information with supply chain members on a project[20]. The different amounts of data are termed Levels of Definition. The amount of non-graphical information developed for a given stage is termed “Level of Information” or LOI and the amount of graphical information developed is termed “Level of Detail” or LOD. Both form part of the overall umbrella term; “Level of Definition” [8,21].

4.2.10 Challenges with project LOD increment

Based on what is illustrated in Table **4-2** and Table **4-9**, generally developing a BIM model to higher LOD will support more different uses or applications of BIM information in projects.

However, managing that higher LOD model is challenging for two main reasons, the issue of associated risks and the issue of interoperability/data-exchange challenges. In brief, the higher the LOD of the model used in BIM collaboration, the more accountability will be required for the accuracy of the model and its contained information. Also, while higher LOD models can convey more detailed information, they can also lead to undesirable exposure of Intellectual Property (IP) which can lead to questions about the ownership of the information [22]. Industry best practices address these issues by relying on precisely developed BIM project execution plans, including specified LOD transfer expectations and agreements, to mitigate these IP risks and help clarify the ownership of the models.

By observing the existing use of BIM design authoring tools, it was noted that higher LOD models are mainly developed and created using customized libraries and proprietary parametric 3D objects enabled by those BIM tools. When exchanging these models, they often need to be transformed to non-parametric 3D models. Although these 3D models may still support some BIM applications where the accuracy of the geometry is important (such as 3D coordination for clash detections), the transformation often results in the loss of non-geometric information values and thus utility. Improved data-exchange protocols and continuing development in model exchange standards could reduce this loss of information and utility.

4.3 Optimization in Level of Development (LOD)

As mentioned earlier, the primary goal of this research is to identify the proper LOD level per application. Given the industry application, the best LOD is the one that is the most efficient. The one that best balances the costs of creating a model at that LOD and the returns or benefits received through the use of the model. This section outlines how this balance was determined.

4.3.1 Methodology

Looking at the instructions for selecting LOD levels included with AIA and other BIM guidelines, it can be seen that the range of possible applications of BIM in a project generally increases as the LOD of the project BIM model increases (Table 4-2 and Table 4-9). However, as was mentioned earlier, increasing the LOD can significantly increase modeling time and costs. The long-term goal for the authors is to develop an automated BIM design system which could be deployed by PEB industry. One of the main challenges in the development of such an automated BIM modeling system is to define the input and output for the system. In other words, to define what sort of initial information to input into the design algorithm and how much automation is required to create model output with a certain (targeted) LOD.

Fig. **4-4** shows two paths for model development from low to higher LODs developed by the authors when studying the PEB domain. This graph was created by the author, based on industry observations and thesis research development, to better illustrate and elaborate on the existing challenges and the main problems to be addressed. Similar trade-off curves between increasing model LOD (and thus increasing model utility) and model development time and costs play out in other construction sectors (discussed in [1]-chapter 5 of this thesis). One logical approach for obtaining a hypothetically optimum LOD point involves finding the point along the curve where additional costs begin to outweigh returns.

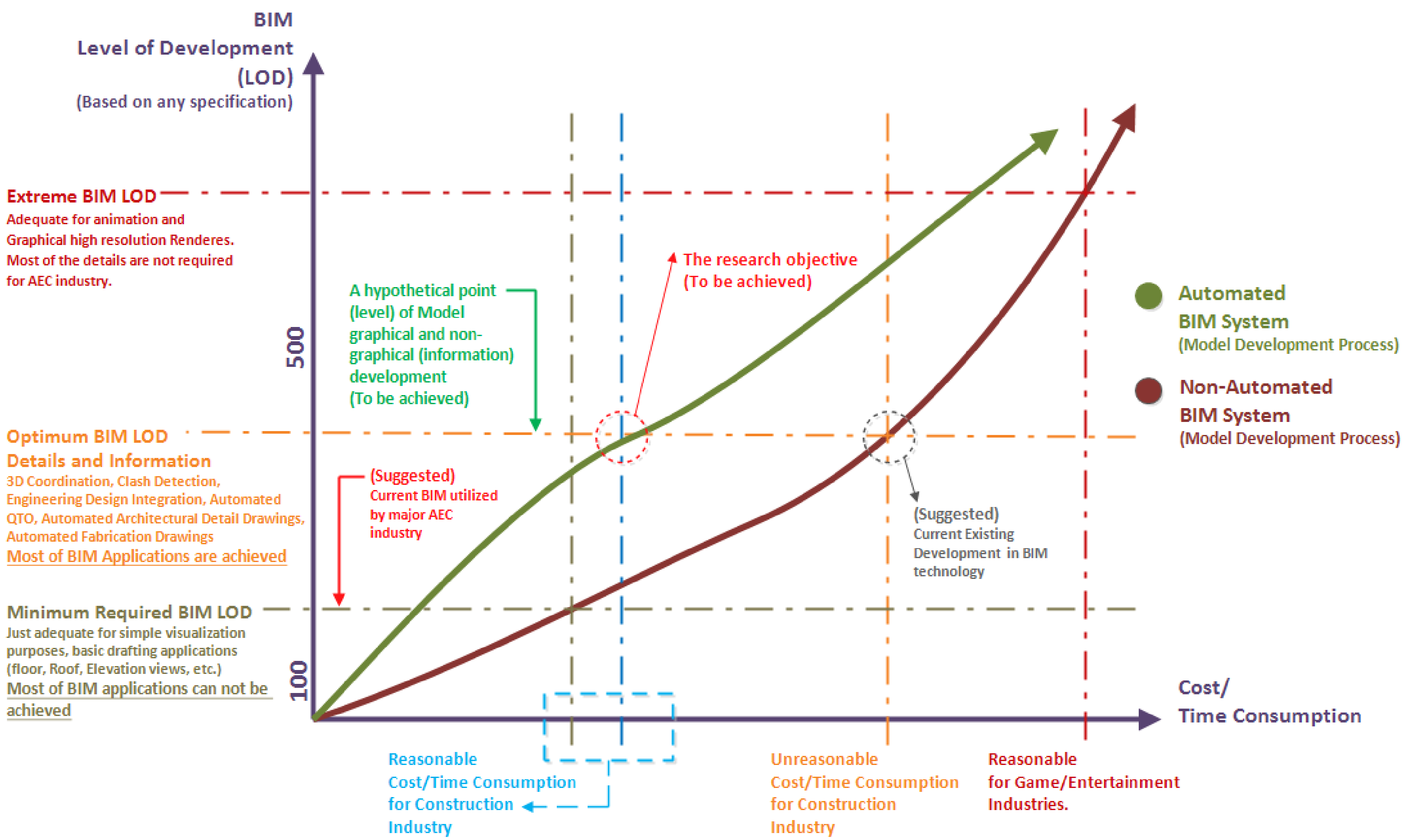


Fig. 4-4 - Research objective illustration- LOD vs. Cost/Time Consumption ([1]-chapter 5) of this thesis (developed by author)

The vertical axis in Fig. 4-4 shows how an increase in possible BIM applications corresponds with an increase in model LODs (see also Table 4-2 and Table 4-9). The horizontal axis depicts the costs of achieving the desire LODs. Hence, the methodology of this research is to establish a trade-off between the two. The results of such comparison could indicate/suggest how much value for a project could be earned at each level of LOD. However, the contents of Table 4-2 and Table 4-9 only describe the BIM applications at a general level which makes linking LODs to the results of industry surveys on the benefits of BIM applications difficult and somewhat problematic in value.

After studying the results of different BIM surveys vs. BIM guidelines, the authors found a logical relationship between commonly defined BIM applications, industry benefits, the frequency of use of these applications, and LOD requirement for such applications. This relationship was obtained by assembling the Penn-State BIM guideline for BIM applications[23], results of a research on the frequency and benefit of those BIM applications[24] and BIM guidelines for required LOD for achieving those BIM applications (by New York City, Department of Design and Construction) [25] all together. Also, to further validate the benefits of the various BIM applications, the resulting data was cross-referencing against the results of a survey on Return on Investment (ROI) of BIM applications published by McGraw-Hill Construction (SmartMarket Report) [26], discussed later in this paper.

4.3.2 BIM applications frequency of uses and benefits

Among various BIM guidelines, Penn-State has provided one of the best BIM execution plan development guidelines. Their guidelines specify the various BIM applications through different project phases, define the BIM workflows and describe the BIM roles and LOD developments using a model element table[23]. Research (survey base study) by Ralph Kreider et al. was conducted based on the Penn-State BIM guideline on determining the frequency and impact of applying BIM for different purposes on projects[24]. The results of the research are presented in Table 4-10.

Table 4-10 - BIM uses Vs. Frequency of use and Benefits

BIM USE	Frequency	Rank	Benefit	Rank
	%	1 to 25	-2 to +2	1 to 25
3D Coordination	60%	1	1.60	1
Design Reviews	54%	2	1.37	2
Design Authoring	42%	3	1.03	7
Construction System Design	37%	4	1.09	6
Existing Conditions Modeling	35%	5	1.16	3
3D Control and Planning	34%	6	1.10	5
Programming	31%	7	0.97	9
Phase Planning (4D Modeling)	30%	8	1.15	4
Record Modeling	28%	9	0.89	14
Site Utilization Planning	28%	10	0.99	8
Site Analysis	28%	11	0.85	17
Structural Analysis	27%	12	0.92	13
Energy Analysis	25%	13	0.92	11
Cost Estimation	25%	14	0.92	12
Sustainability LEED Evaluation	23%	15	0.93	10
Building System Analysis	22%	16	0.86	16
Space Management / Tracking	21%	17	0.78	18
Mechanical Analysis	21%	18	0.67	21
Code Validation	19%	19	0.77	19
Lighting Analysis	17%	20	0.73	20
Other Eng. Analysis	15%	21	0.59	22
Digital Fabrication	14%	22	0.89	15
Asset Management	10%	23	0.47	23
Building Maint. Scheduling	5%	24	0.42	24
Disaster Planning	4%	25	0.26	25

4.3.3 BIM Return on investment (ROI)

It is very difficult to find rigorous and comparable measures of the economic benefits of BIM use in academic publications, but there are some white papers and technical reports of BIM related applications, guidelines, and reports generated by government and other regulatory bodies based on the results of broad annual surveys. These non-academic publications, particularly the one published by McGraw-Hill Construction (MHC) [26], are the most respected publications on the current state of BIM adoption in the industry [27]. The result of the 2012 survey by MHC on North American construction on elements which improve ROI for BIM users by players is presented in Table 4-11[26]. (Note the assignment of letter designators to the table column and row headers is for use in the next stage of analysis.)

Table 4-11 - Elements that improve ROI for BIM users by Players[26].

Elements That Improve ROI for BIM Users by Player

Source: McGraw-Hill Construction, 2012

		a	b	c	d	e	f	g	h	i	j
		Improved Job-Site Safety	Positive Impact on Sustainability	Positive Impact on Staff Recruitment and Retention	Faster Plan Approval and Permits	Increased Prefabrication	Lower Project Cost	Reduced Cycle Time for Project Activities and Delivery	Better Multi-Party Communication	Improved Project Process Outcomes	Improved Personnel Productivity
A	Architect	13%	47%	46%	35%	19%	62%	68%	74%	74%	79%
E	Engineer	13%	20%	28%	28%	22%	41%	50%	65%	59%	59%
C	Contractor	57%	36%	37%	48%	81%	78%	79%	71%	81%	85%
O	Owner	33%	67%	17%	50%	50%	83%	50%	100%	100%	50%
	TOTAL	33%	37%	37%	40%	48%	65%	68%	71%	74%	77%

More than 75% | 51% to 75% | 26% to 50% | 25% or Less

MHC survey results are based on the player (different project stakeholders/disciplines) and they need to be interpreted and related to the BIM uses as defined by Penn-State guideline (for BIM roles in different project phases) [23] for further analysis.

4.3.4 LOD requirements of BIM applications (benefit/advantages)

The New York City Department of Design and Construction (DDC) BIM Guide[28] provides guidelines for the consistent development and use of BIM across multiple building types and a wide range of municipal agencies. Furthermore, this guide will be useful for any agency or organization that may be interested in utilizing BIM for public projects. An interesting effort has been made by this guideline to utilize AIA E202 LOD specification alongside with Penn-State instruction for BIM uses and workflows to develop an instruction for the minimum required LOD for each construction element in model element table to achieve BIM applications categorized by Penn-State guideline[25].

In an effort to find an optimum LOD, authors combined the NYC guidelines with the results of the research on benefits and frequency of BIM uses. The LOD recommendations given in the NYC guideline is presented in Table 4-12.

Table 4-12 – Suggested minimum required LOD vs. BIM uses by NYC guideline

100	Pre-Schematic (LOD 100)	Existing Condition Model
100		Site Analysis
100		Space Program
100		Design Authoring - Volumetric Model
100		Zoning and Orientation
200	Schematic (LOD 200)	Design Authoring - Preliminary Model
200		Sustainability (LEED) Evaluation
200		Programing
200		Phase Planning
200		Preliminary Cost Estimate (Square Footage)
200		Design Review
200		Preliminary 3D Coordination
300	Design Development (LOD 300)	Design Authoring - Model
300		Sustainability (LEED) Analysis
300		Detailed Energy Analysis
300		System Cost Estimates
300		3D Coordination Reporting
300		Program Validation
400	Construction Documents (LOD 400)	Design Authoring - Final Model
400		3D Coordination Validation
400		Cost Estimation
400		Sustainability (LEED) Reporting
500	Services During Construction (LOD 500)	Construction System Design
500		Phase Planning
500		Digital Fabrication
500		Record Modeling
500		Asset Management

Penn-State guideline was used to define the role of each project stakeholders and to relate them to the elements that improve ROI based on Table 4-11. The concluded comparison and results are presented in Table 4-13.

Table 4-13 - Required BIM LOD vs. Project ROI, Attained Benefits, and Frequency of uses based on the Penn-State definition of BIM uses

BIM USE	LOD Requirement	Players	Elements That Improves ROI	Averaged improved ROI	Frequency	Benefit (-2 to +2)	Benefit (Percentage)
3D Coordination (Report)	300	A,E,O,C	f,g,h,I,j	71%	60%	1.6	100%
Design Reviews	200	A,E,O,C	f,g,h,I,j	71%	54%	1.37	86%
Design Authoring	200	A,E	I,d	49%	42%	1.03	64%
Construction System Design	500	O,C	f,i	86%	37%	1.09	68%
Existing Conditions Modeling	100	A,E	I	67%	35%	1.16	73%
3D Control and Planning	200	C	f,g,i	79%	34%	1.1	69%
Programming	200	A,O	g,I,j	69%	31%	0.97	61%
Phase Planning (4D Modeling)	300	C	f,g,i	79%	30%	1.15	72%
Record Modeling	500	E	f,g,I,j	52%	28%	0.89	56%
Site Utilization Planning	100	C	a,j	55%	28%	0.99	62%
Site Analysis	100	C	a,j	55%	28%	0.85	53%
Structural Analysis	400	E	b,f,I,j	45%	27%	0.92	58%
Energy Analysis	300	E	b,f,I,j	45%	25%	0.92	58%
Cost Estimation	400	C,O	I,j	79%	25%	0.92	58%
Sustainability LEED Evaluation	300	E,O	b,f	53%	23%	0.93	58%
Building System Analysis	300	E	b,f,I,j	45%	22%	0.86	54%
Space Management / Tracking	300	C	j	85%	21%	0.78	49%
Mechanical Analysis	300	E	b,f,I,j	45%	21%	0.67	42%
Code Validation	200	A,E	d,j	50%	19%	0.77	48%
Lighting Analysis	200	E	b,f,I,j	45%	17%	0.73	46%
Other Eng. Analysis	400	E	b,f,I,j	45%	15%	0.59	37%
Digital Fabrication	500	C	e,f,g,I,j	79%	14%	0.89	56%
Asset Management	500	O	i	50%	10%	0.47	29%
Building Maintenance Scheduling	500	O	i	50%	5%	0.42	26%
Disaster Planning	500	O	i	50%	4%	0.26	16%

4.4 Results and discussion

Fig. 4-5 presents Table 4-13 in a graphical form in to illustrate better the results of the comparison of Frequency, Benefit, and ROI against model LOD requirements as extracted from the industry surveys. The impact number for each LOD was calculated by averaging the percentages in the blue, orange and gray columns from Table 4-13 for entries with matching LOD requirements column.

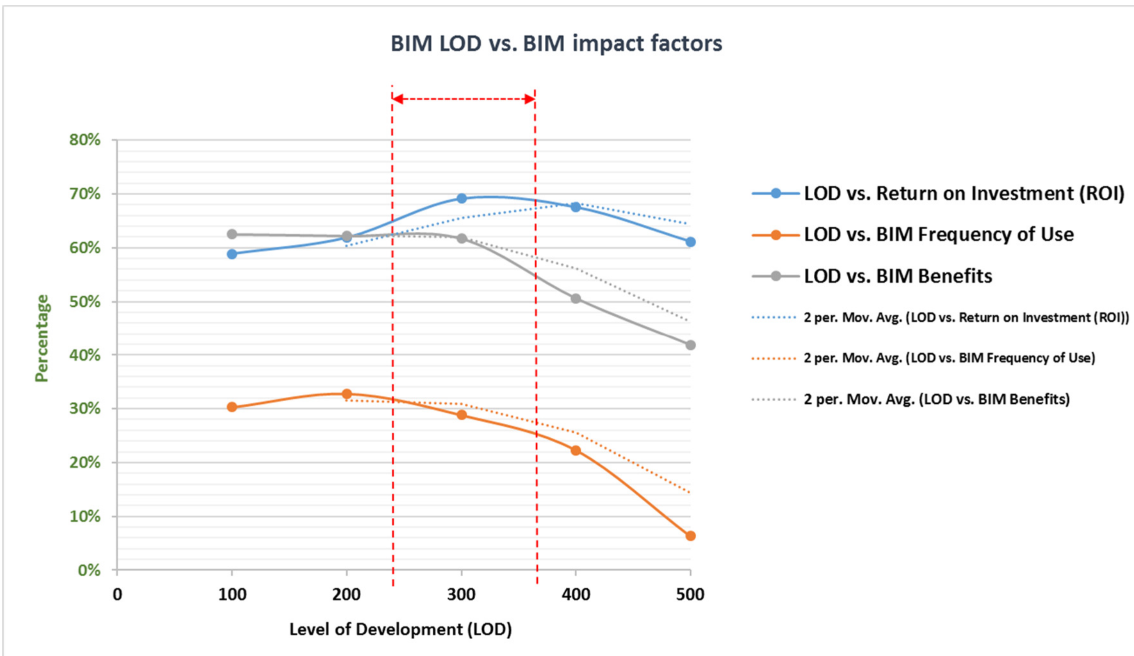


Fig. 4-5 - BIM LOD vs. Impact factors

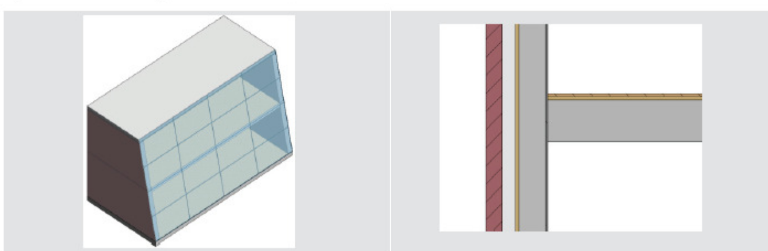
Analysis of survey results indicates that most BIM models are currently developed to LOD200 in the broader AEC industry. This analysis seems reasonable when looking at the rate of BIM implementation in AEC industry over last decade[29]. BIM started as a design collaboration tool[1]. Hence all project delivery stakeholders must deploy and implement BIM to some degree to achieved the greatest benefit. Fig. 4-5 also shows that higher LOD BIM models yield lower ROI (often attributed to technical issues, such as interoperability problems). For example, results of the survey indicate creating higher LOD models for other engineering analysis yields only a 37% (0.59/1.6) benefit score in comparison to a 100% benefits score for “3D coordination applications”. This reflects the time, cost difficulties and limited capabilities in dealing with BIM models with higher LODs as mentioned earlier in this paper. Based on Fig. 4-5, one can conclude that a project can benefit the most from BIM utilization when the target LOD is 300.

However, readers should note that the overall possible Return on Investment (ROI) is higher when higher LOD BIM model can be used for further applications such as shop drawings, clash detection, and facility management. To realize these returns the technological challenges and costs associated with achieving and using LOD models higher than 300 will need to be addressed (see the drop in ROI after LOD 300 in Fig. 4-5). In a separate publication, the authors address this by implementing and assessing a BIM-based framework for automated design for the PEB sector.

For the current state of technology and processes in the general construction industry, Fig. 4-5 indicates that the best ROI (i.e. optimum) can be achieved by utilizing LOD300. Thus, the AEC industry should be encouraged to target using LOD300 models as a starting point. The same LOD300 level was also selected as the initial target output in the PEB evaluation project discussed in the next section. For clarity, the NYC guideline for LOD300 is presented in Fig. 4-6.

LOD 300

Level 300 Models include elements in which Generic Components have been replaced with fully defined Assemblies. Analysis based on Specific Systems can be performed. Quantities based on Materials can be obtained.



Wall Material Takeoff (LoD-3)	
Material: Name	Material: Volume
Gypsum Wall Board	58.66 CF
Masonry - Brick	425.26 CF
Metal - Stud Layer	703.87 CF
Misc. Air Layers - Air Space	351.94 CF
Wood - Sheathing - plywood	87.98 CF

Fig. 4-6 - An illustration and discerption of LOD300 by NYC guideline

For consistency, all the data used for this comparison were obtained from surveys executed around the same date (around 2012) although in some cases newer survey results are available. Although it is expected that the trends in ROI and BIM use will change over time, a quick review of more recent periodic surveys indicate the current status of BIM adoption has remained similar for the last couple of years[29].

4.4.1 Example PEB Project

To evaluate the application of the “Optimum LOD” as an achievable and useful output for alternative construction domains a PEB project was used as a test case. The design tool used for the evaluation was a BIM-based automated design system developed by the authors to assess a proposed BIM framework for PEB industry, as discussed in ([1]-chapter3) of this thesis. This BIM framework makes use of automation to facilitate the design development similar to current commercial PEB design systems. The BIM design tool for PEB was developed as a customized PEB design and automation interface that accesses the Autodesk Revit modeling software through its API. An illustration of the design parameter input process using the custom interface is shown in Fig. 4-7.

An example PEB project reviewed was for a real industrial PEB building that had previously been designed and developed using traditional non-BIM PEB design tools. The design of this 21m x 16m x (11.53m Eave Height) Gas Compression Station was done in the absence of any BIM model for the PEB structures, the building enclosure, and without a collaborative design environment. The example project was illustrated in Fig. 3-11 of chapter 3 of this thesis.

One application of the example PEB project, developed for this research, is to investigate the performance and feasibility of the “Floating LOD” concept. In addition, this case study illustrates the results of using LOD 300 as the initial target/output for the automated design process for a typical PEB project. The sufficiency of LOD 300 as defined optimal LOD for two main BIM applications (BIM-based Material quantification/Procurement system and BIM integration for engineering design) are discussed separately in next chapters of the thesis.

Parametric 3D models (grouped into "families") and the capability to store LOI information are already incorporated in BIM tools such as Autodesk Revit as of-the-shelf features. However, for implementation of the Floating LOD concept, a detailed process map and algorithm were developed to introduce the system families (Wall, Roofs, etc.) in the form of information (increasing LOI) for the BIM design authoring tool through developed API interface (illustrated in **Fig. 4-7**). Also, additional data were programmatically stored in a BIM database as "shared parameters". In the end, the automation and Floating LOD processes were coded in an add-on application using the Revit API to turn system specification information into 3D geometries using stored information and parametric models.

The feasibility evaluation and assessment through example project are one of the main research contributions. The code and the process can be used for BIM technological development in the form of software development.

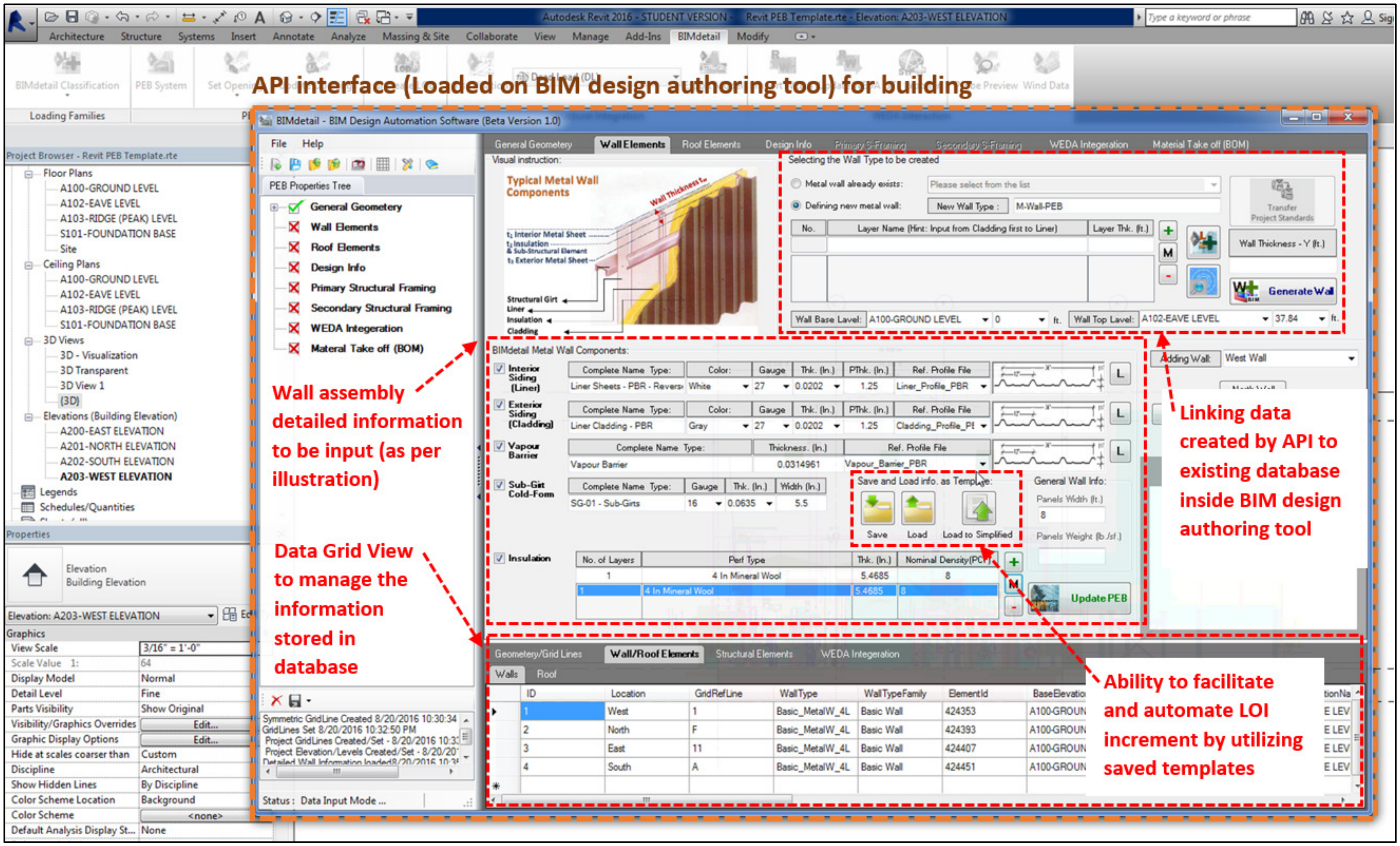


Fig. 4-7 - PEB BIM API software interface for information (wall element) input regarding ([1]-chapter3) of this thesis.

As mentioned earlier, the PEB software initially aims to achieve an approximately LOD300 CAD model as an output. At this LOD level, "models include elements in which Generic Components have been replaced with fully defined Assemblies. Analysis based on Specific Systems can be performed. Quantities based on Materials can be obtained" [25]. Testing showed the tool could quickly develop the target LOD models, and that they demonstrated all the desired properties necessary to support the expected BIM applications. In other words, the results confirmed that good ROI was achievable with LOD300 models in the PEB domain, illustrating that the Optimum LOD for the general construction sector is a good initial LOD in other, more specialized, construction domains as well.

Note, however; subsequent model development would be needed to achieve the higher LODs necessary for more advanced model applications such as accurate interference studies, 2D detailing, accurate non-structural (tertiary elements such as flashings and capping) design. Readers are referred to ([1]-chapter3,6 and 7) of this thesis, to review how automation in the PEB sector could shift the optimal LOD to be higher than LOD300 through the effective application of automation. Further application of automation to achieve these improvements requires addressing a number of challenges beyond the scope of this publication.

4.5 Conclusion

The aim of this paper was to discuss the BIM Level of development (LOD) and its implications and to review some of the existing challenges with LOD application in industry. By relating LODs to various industry applications of BIM and their associated ROIs and benefits, it was possible to develop a couple of curves that show that a LOD of 300 is a broadly good, if not optimal level for model development considering the trade-offs of benefits versus costs for the general construction industry.

It was also observed that currently most BIM users only develop BIM models to LOD200 which is short of the identified LOD300, probably limiting the potential ROI for their projects. Analysis of the data also showed that current BIM technologies and user's ability to handle highly developed models while performing design and analysis tasks contribute to the lower ROIs experienced when working with higher LOD models. If these challenges could be overcome, higher LOD and commensurately more advanced BIM applications would become worthwhile in terms of ROI. An approach for ameliorating these challenges has been developed by the authors and is discussed in a separate publication ([1]-chapter3) of this thesis.

Acknowledgement

The authors would like to show their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was developed.

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Chapter 5

5 Automation in Building Information Modeling (BIM) process; An example Pre-Engineered Building project

Abstract

Over the last decade, the construction industry has been challenged with upgrading its "design to operation" processes; from traditional blueprint system to Computer Aided Design (CAD) and now to Building Information Modeling (BIM). The BIM system offers an opportunity to automate the different process in a project throughout its design to process lifecycle. This paper reviews a number of BIM applications that automate the project design to operation processes. A Planar Concept approach that allows for the automation of BIM model development processes is proposed in order to increase the detail of the model. This is expected to allow the extra use of model information without excessive modeling costs. The difficulties in developing such automation for BIM without limiting the BIM capabilities and customizing the general BIM design and construction industries are discussed. The ability to relate/link model elements to larger systems and switch between representations as well as the ability to generate both a design and analytical models in parallel are important in automation of engineering design. Finally, to evaluate the feasibility of the developed concepts and algorithms for automating the BIM model development, an API BIM-based software was developed by authors. The success in implementation of the API software was examined through developing a BIM model for an example PEB.

Keywords:

Building Information Modeling (BIM), Automated BIM Processes, Planar Association concept, Application Based Classification Approach, Design Customization flaws, Pre-Engineered Building (PEB)

5.1 Introduction

The recent results of internationally trusted BIM surveys indicate a significant increase in BIM awareness and motivation for the adoption of BIM by the general built asset industry[1,2]. In fact, in the 2015 NBS report, there was an increase of 13% to 48% in BIM awareness in the UK between 2010 to 2014[11]. However, issues such as transitioning from 2D CAD systems to BIM and the continued lack of required competencies in the design team to deploy BIM technologies remain a major problem impacting BIM implementation internationally. These two issues have been indicated as the main barriers that prevent the practical implementation of BIM[4,5]. Challenges associated with BIM deployment are not only related to software limitations but also to a technological shift that includes new procedures, roles, workflow and data exchange plans that must be defined. However, the lack of understanding of how to properly develop a BIM model is mainly due to technical challenges [4]. A BIM model must be developed to a certain Level of Development (LOD), to be utilized as an effective asset such that most of its applications for projects are achieved [6–8]. However, the development of a BIM model to an advanced LODs is costly and a time-consuming process. Hence, the "efficiency" of current BIM procedures, particularly the model development process, is the primary concern in the successful implementation of BIM.

The main research objective is to develop a BIM framework for the PEB industry. This BIM framework adapts the existing automation in traditional PEB design to include aspects of the Pre-Fabrication BIM processes [11,12]. This paper introduces a new concept that includes the automation of BIM model development and engineering design integration processes used within the PEB sector. This paper discusses how this concept to facilitate the broader use of automation in general BIM design processes could be adopted by the AEC industry. In the present context, the "Process automation" is a general technological term that is used to describe all processes that are automated by computer software. Processes that have been automated are performed faster and require less human intervention[9]. There are two concepts that can lead to the successful implementation of BIM and allow for more automation inside the BIM processes[10]. Firstly, the automation that the utilization and implementation of BIM can bring to the general AEC industry.

Secondly, the automation which can be developed/implemented inside the BIM system, to facilitate the BIM utilization. To clarify these issues related to the BIM automation, both concepts are reviewed and discussed in this paper.

5.2 BIM applications and automation throughout the lifecycle of a project

There are several publications that comprehensively discuss the benefits and applications of BIM during different phases of a project [11,13–14]. These applications are not further discussed in this paper. However, varying automation approaches that could apply to the different phases and uses of BIM in a construction project are briefly discussed in this paper.

5.2.1 3D model creation

Initially, BIM was introduced, as an architectural design tool. Elements in BIM have intelligent properties and attributes. Over time, the time-consuming process of creating 3D models from 2D layouts was replaced with the use of semi-automated parametric 3D objects. Also, BIM design systems allow users to manipulate a central 3D model in real-time using different 2D views (i.e., floor plan, elevation and section views) thus significantly easing and facilitating the creation of 3D models[15,16]. Although model editing is facilitated by these parametric models, the automation of the development process itself could achieve certain required LODs, such as the generation and placement of components that make up higher level systems or assemblies (like walls or structural framing). Such automation has the potential to increase the efficiency of the existing BIM design systems and help foster BIM implementation for the general construction sector.

5.2.2 3D Coordination and Conflict and clash pre-detection

One of the main benefits of BIM during the design and construction phases of a project is 3D coordination. Through the process of 3D coordination, interference issues such as overlapping geometry can be avoided before construction. Also, site issues and Request for Information (RFIs) can be resolved through the use of a review process that uses BIM's 3D modeling environment [14,17]. BIM develops and utilizes 3D models that are not only collections of geometry but are elements representative of building components. Because of this, BIM “design review software” (i.e., Autodesk Navisworks [18]) can identify overlaps a well as the building components involved. Hence, BIM automates this process of clash detection and minimizes human intervention. This is important because in many complex designs, manually detecting clashes throughout the project is a tedious and somewhat impossible task.

5.2.3 Design workflows

When a BIM model is developed as a proper LOD, different construction disciplines can collaborate using the same model. BIM models that are developed for architectural design or visualization purposes can be utilized for further design applications such as structural design and analysis (e.g. building code compliance), or mechanical/electrical design and analysis (e.g. energy modeling, duct working design, or electrical conduit planning). BIM not only streamlines the process of design by eliminating the recreation of a model, but it can also provide more accurate monitoring of the progress of the design process using recently introduced tools such as Autodesk Vault[19,20] by tracking the transfers of BIM models between individuals in different disciplines[21]. Despite the improvements, interoperability and incorrect model development processes still, prevent the improvement of BIM. A method to overcome a number of these difficulties is introduced in this paper.

5.2.4 Design drafting and fabrication output

Of all the ways BIM has been used to support construction projects, the surveys in the 2012 and 2014 SmartMarket Reports [1,22], indicate that automation in fabrication and increased use of pre-fabrication have shown to deliver the best Returns on Investment (ROI). The major problem with developing the shop drawings using CAD systems is the extensively iterative process, particularly when the designed elements are exposed to several modifications. Changes in the design of one element in an ‘assembly’ could cause a n unintentional cascading change across many neighboring elements. In contrast to CAD systems, BIM can more elegantly propagate the impact of a change order across a design based on the defined logical relationships between model elements. For example, the relocation of columns can extend the structural beam between two columns. Therefore, manually created 2D CAD shop drawings are replaced with columns based on logically consistent BIM models. Architectural drawings/General Arrangement (GA) drawings, which include a defined tolerance, are less sensitive to design changes. However, BIM can produce 2D drawings from 3D models faster and in a more automated and repeatable way than manually operated CAD systems. This can include some drafting tasks such as inserting annotations on elements that need annotations (such as walls, doors, windows, etc.).

5.2.5 Material quantification, Bill of material (BOM) and procurement system

When a BIM model at a proper LOD is available, software tools can calculate the quantity of the building materials required. This application is very beneficial for pre-fabrication processes and construction industries such as PEB and pre-fab depend on this capability ([6]-chapter 2 of this thesis). As BIM elements are recognizable to software due to their attached information tool, data can be extracted by category and generate structure schedules or reports instantly. A separate publication contains details on work done to further develop automated processes in support of material quantification and procurement documentation management in a BIM coordinated procurement system ([6]-chapter 7 of this thesis).

5.2.6 Project management and reverse modeling (Scan to BIM)

Most applications of BIM are achieved by linking information in databases to the 3D BIM models. Different types of information can be linked to a 3D model to enhance its capabilities such as project schedule (4D models), building element costs (5D models) and so forth. The linked information would help project stakeholders such as managers and owners achieve better project planning[23]. Research by Y.Turkan et al. [24] suggest that project management can be more automated through "Scan to BIM" (3D reconstruction). This research proposes different digital approaches for automated comparison between the BIM 3D models and the 3D point clouds obtained from the project site, to estimate the project progress. In addition, through the advanced algorithm, those point clouds could be automatically turned into BIM models that could be used as 3D "as-built" models for facility management purposes alongside higher LOD BIM models.

5.3 Automation of BIM processes

Fig. 4-4 summarizes why this research was undertaken to automate the BIM model development process. Model development in the BIM design environment consists of two main steps. Step one is to prepare or acquire a library of components/model elements, at a proper Level of Development (LOD), that design is built from. The second step is to evaluate the iterative assembly of the design from this library of elements. Traditionally, lower LOD models are placed manually by the user, and their properties only can be manipulated later.

As it is illustrated in Fig. 4-4 (in chapter 4 of this thesis), the general objective for automating the process in this research was to reduce the time required for a BIM model to be developed to a LOD that supports many of the desired uses of the model for a project. According to M.Delavar et al. ([6]-chapter 4 of this thesis) , it is suggested that LOD300 (Based on AIA, G202, and NYC guideline specifications)[8,25] can be targeted as an appropriate initial output for an automated design process, while the input for the process could be any lower LOD and Level of Information (LOI).

Several possible automation approaches were examined and two mechanisms were jointly adopted. The first, "Floating LOD" was conceived to have automatic generation and removal of subcomponents of design systems (like walls, or roofs) to allow easy switching between LODs (e.g. low LODs would specify a wall, high LODs could specify all elements in it). This would support modifying designs to meet change requests like "the window needs to be shifted 2 inches left and resized" without manually editing at the subcomponent level (see ([6]-chapter 4 of this thesis). In short, this approach can be described as a generalization of using BIM attributes and parametric families (i.e., doors, windows, kitchen utilities) and applying them to main construction systems (system families by Autodesk's definition[26]) and readers are referred to [6]-chapter 4 of this thesis, for an expanded discussion of the approach. The second mechanism was the "Planar Concept" which will be discussed later in this paper.

5.3.1 Customization and Generalization problem

The PEB industry was used as a case study for BIM automation given its shown reliance on pre-fabrication and the existing use of automation in design processes[1,22]. Fig. 5-1 illustrates the PEB design processes

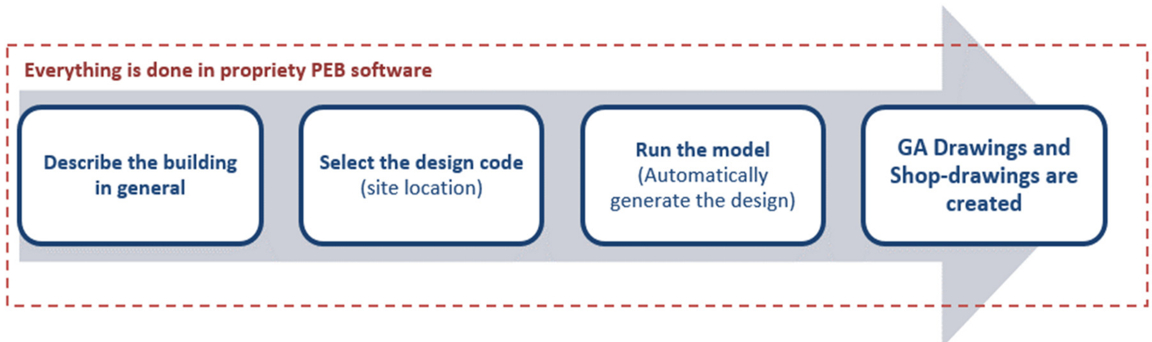

Fig. 5-1 PEB industry design process ([6]-chapter 2 of this thesis)

As Fig. 5-1 shows, the use of a built-in automation computer software only requires the target building geometry and design code information as an input, and it develops the model and runs any required analyses accordingly. The designed building and related drawings are the output of this process. However, as an output, the current software generates a 3D CAD model and users have no control in the process of model developments. Any changes or customization required manual remodeling. Building geometries are limited to default types. Hence, the process is neither collaborative nor flexible. In general, this concept works well for PEB industry players who only deal with simple (one-story) buildings and limited combinations of basic layout shapes. However, the use of design automation to progressively develop a model should be extensible to more customized PEB scenarios and even to the general construction industry. As in the basic PEB industry, such automation would have to include any necessary engineering analysis to generate valid designs and thus eliminate human effort. This is further described in the next three Sections.

5.3.2 Application Based Classification Approach

As mentioned, classifications and parametric descriptions between different LOD representations of building systems need to be defined for the software by the developers of the model families to allow the design process to be automated. One of the relevant classifications that could be defined in construction science is the application of each building element regarding its role in the design, for example, if it is structural.

5.3.2.1 Typical/General construction industry

All building elements can be classified as per their participation in structural load transferring and their location/distance to main load bearing elements. An illustration of such classification for the general construction industry is presented in Fig. 5-2. The main categories are Primary building elements, Secondary and Tertiary building elements, in that order.

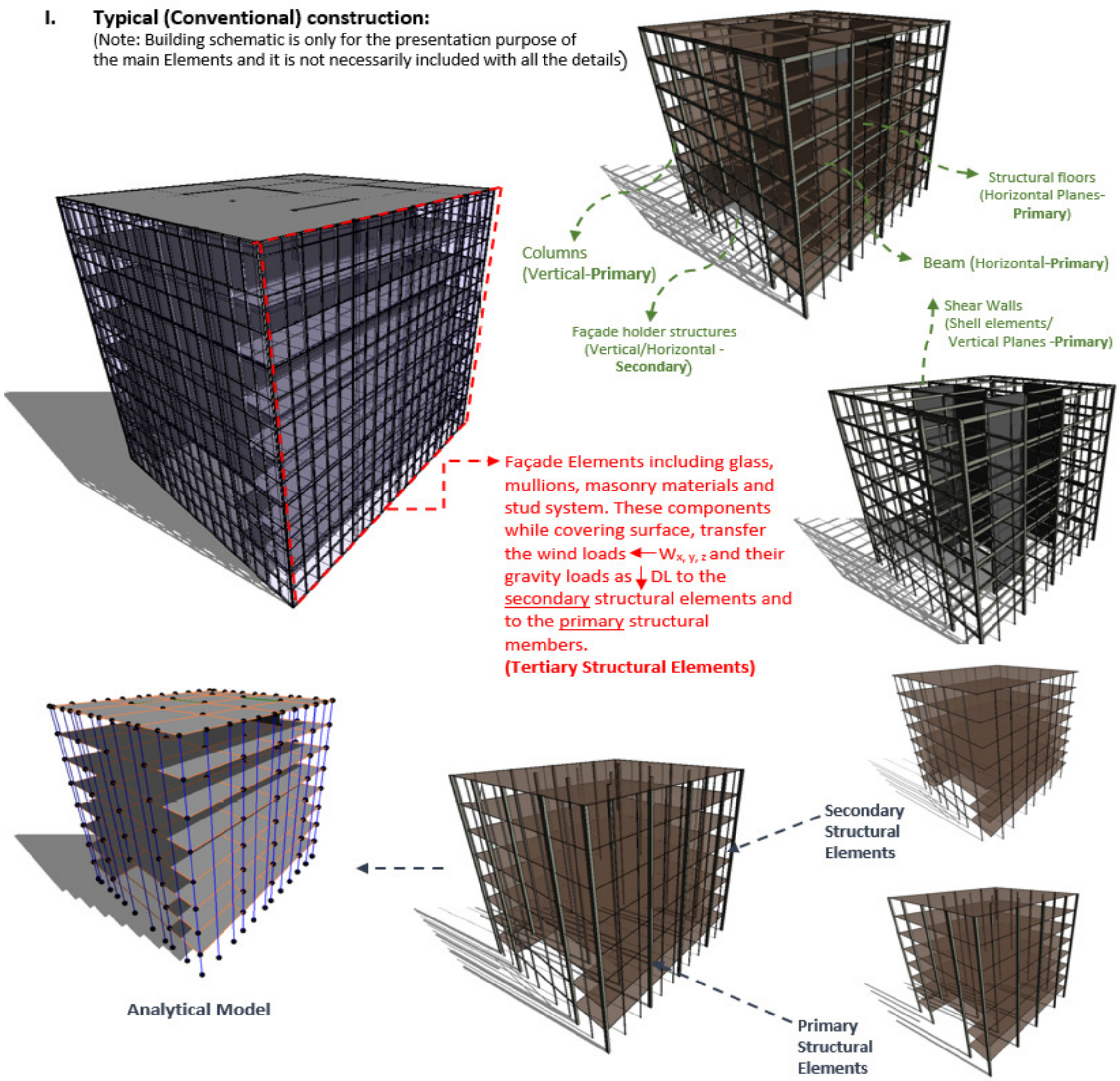

Fig. 5-2 General/Typical building components classification

5.3.2.2 Pre-Engineered Building industry

The PEB industry is more familiar with this classification as traditionally building elements are named and categorized based on their application. Such a classification has been illustrated in Fig. 3-6 (in chapter 3 of this thesis).

5.3.2.3 Defined classification and Structural load transfer logic

The introduced classification follows a logic in load transfer from elements; this classification is illustrated in Fig. 5-3. This logic aligns with the process of element placement in buildings as well, which can allow the BIM process to automate the structural design process internally using the Planar Concept.

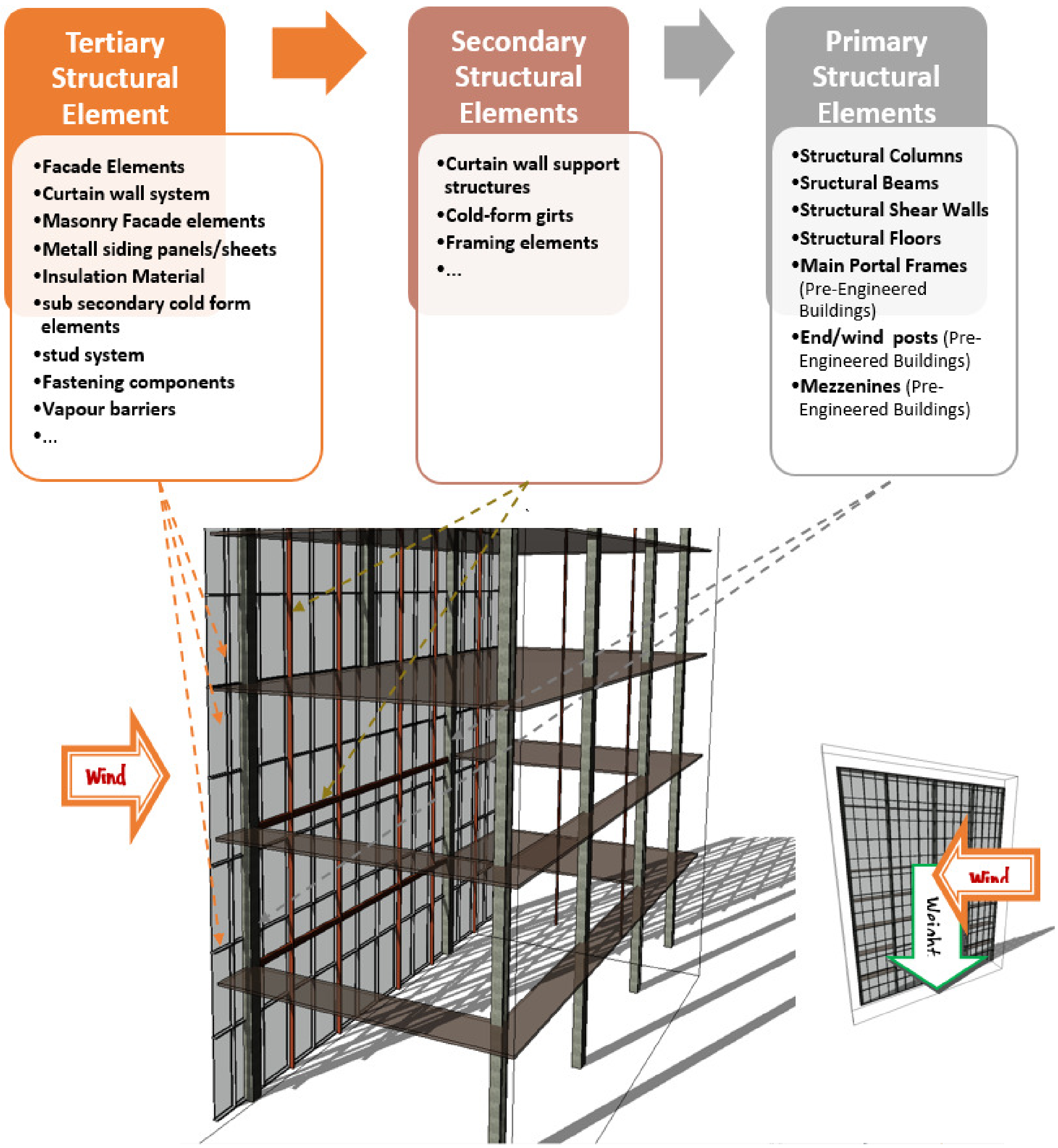

Fig. 5-3 Introduced classification and load transfer logic

5.3.3 Traditional/manual BIM model development process and flaws

Before presenting the Planar Concept approach that uses reference drawing planes for automated placement process, the traditional/manual approach for model placement in BIM is discussed.

5.3.3.1 BIM manual and independent element placement method

The BIM modeling system was considered a revolution for CAD modeling when it introduced the concept of combining information into a database of 3D elements that, when separated, were irrelevant within a design system. The act of adding information to a 3D model is the initial step in creating intelligence in the design system. This concept can be expanded to include not only the 3D model element but also their placements. The idea is that each intelligent 3D BIM model can belong to a referenced element (line or plane). However, as it is illustrated in Fig. 5-4, the traditional modeling approach in BIM begins with a (Step 1) “assisted pick and place” approach in a 3D environment. Therefore, 3D architectural models and dependent analytical/structural models do not necessarily belong to any jointly referenced planes and are thus not linked to one another.

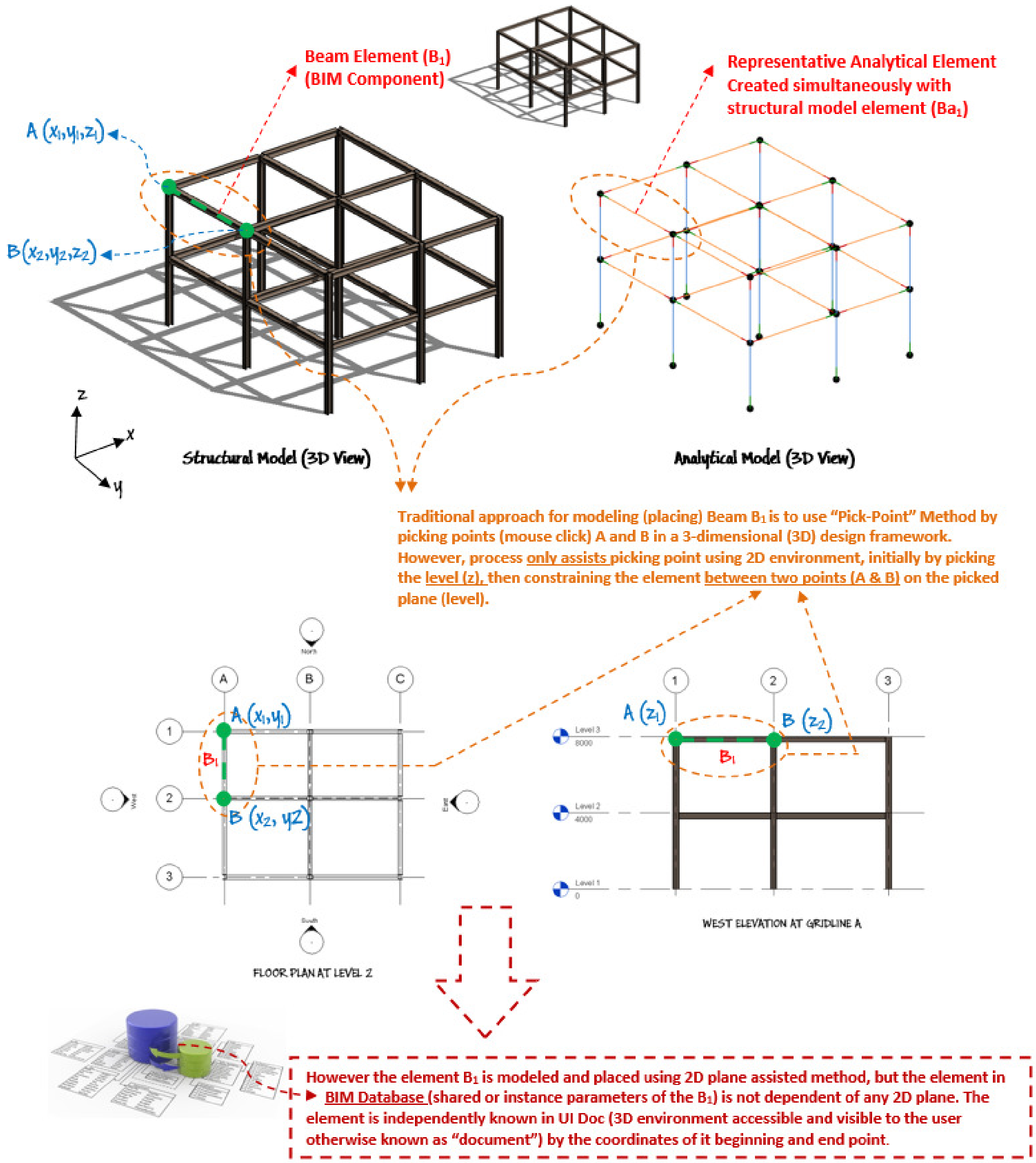

Fig. 5-4 Manual/Independent model element placement example for Step 1 (Primary Structural Elements)

5.3.3.2 Misalignments and inconsistencies in the utilization of traditional approach

The common "assisted pick and place" approach to design, precludes the direct interpretation of the position of analytical model elements. Fig. 5-5 illustrates Step 2, where secondary structural elements are added to the model. As it is illustrated in Fig. 5-5, this step is faced with two main issues with model development. First, when no logic or automation has been utilized, the process of accurately placing the secondary elements (such that all elements are adjacent) can be very time-consuming. Second, these secondary structural elements are placed hypothetically at the center of mass/volume of the architectural elements (if an element is specified to have structural application). As it is illustrated in Fig. 5-5, misalignments, inaccuracies and redundancies may occur at this stage and can make the use of automated/integrated structural design infeasible.

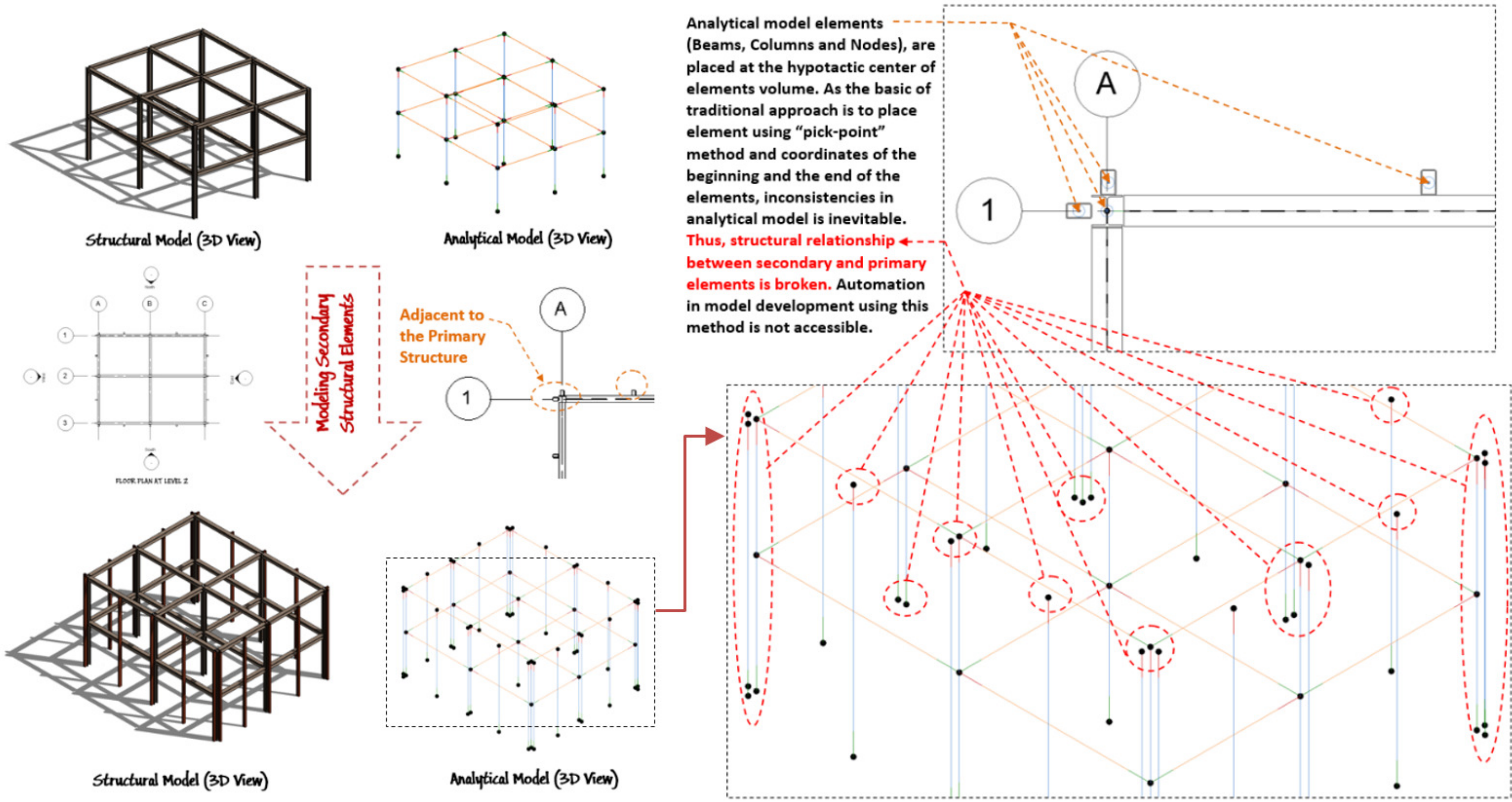

Fig. 5-5 Manual model element placement example for Step 2 (Primary + Secondary Structural Elements)

As it is illustrated in Fig. 5-6, the two mentioned issues can become increasingly problematic as the model progresses to Step 3.

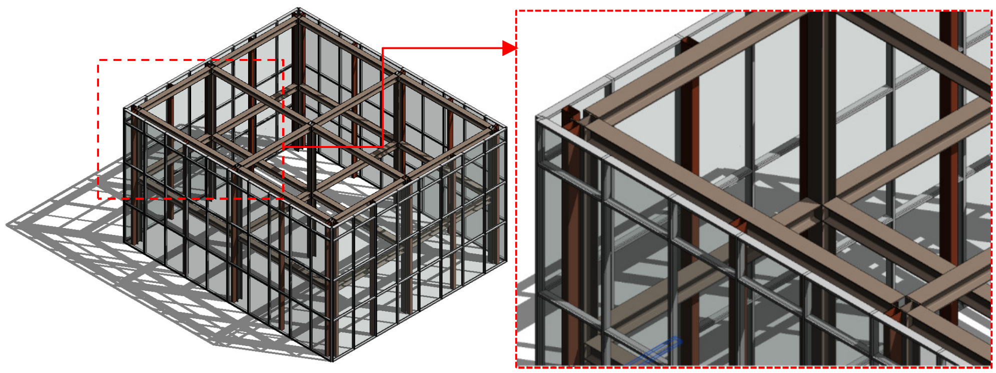

Fig. 5-6 Manual model element placement for Step 3 and further (all building elements)

5.3.4 The Planar Concept

5.3.4.1 Planar Concept Introduction

Engineering analysis is not done with construction or design models, but instead with analytical models. While analytical models are representative of design, they are simplified to perform the desired analysis. In the case of structural models, structural elements in design are often reduced to connect linear elements with the appropriate structural attributes. Elements in these models are often treated as if they are on the same analytical reference plane, even though they might be slightly offset in the actual design and construction. Structural elements in the test application were categorized according to their structural role and the "Planar Concept" was developed to use the classification to allow the software to locate and connect the analytical model to the actual architectural model.

5.3.4.2 Association of a unique reference plane

The proposed Planar Concept suggests referencing the model placements of all the physical and analytical sub-elements to a unique reference plane (Fig. 3-5 in chapter 3 of this thesis).

Traditionally, in computer aided design, reference planes are the model placement helpers for inserting 3D elements into 3D environment using 2D controllers [31]. Fig. 5-7 illustrates how all the building elements can be assigned to a unique reference plane.

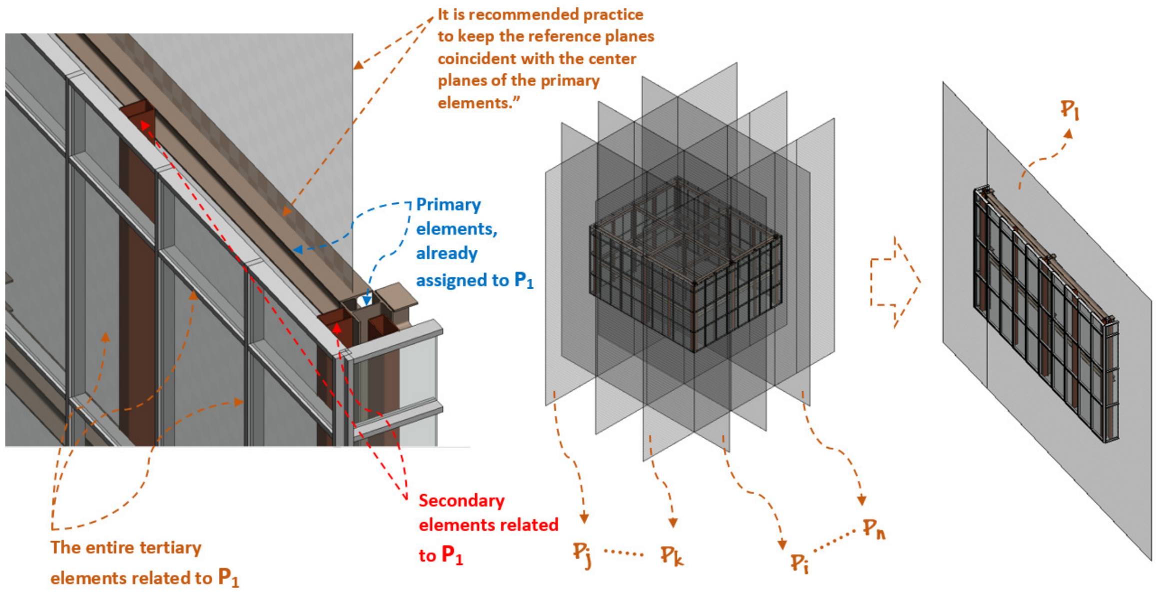

Fig. 5-7 Illustration of the assigned elements to a unique reference plane (P1)

5.3.4.3 Design integration using defined logic for elements relationships (reference plane association)

Recall, from section 3.2, that defining the logic of the relationship between structural elements using reference planes and classifications enables automation for the model development (in element placement processes). Fig. 5-8 shows a restatement of the logic defined for software to implement. The developer/user inputs the classifications.

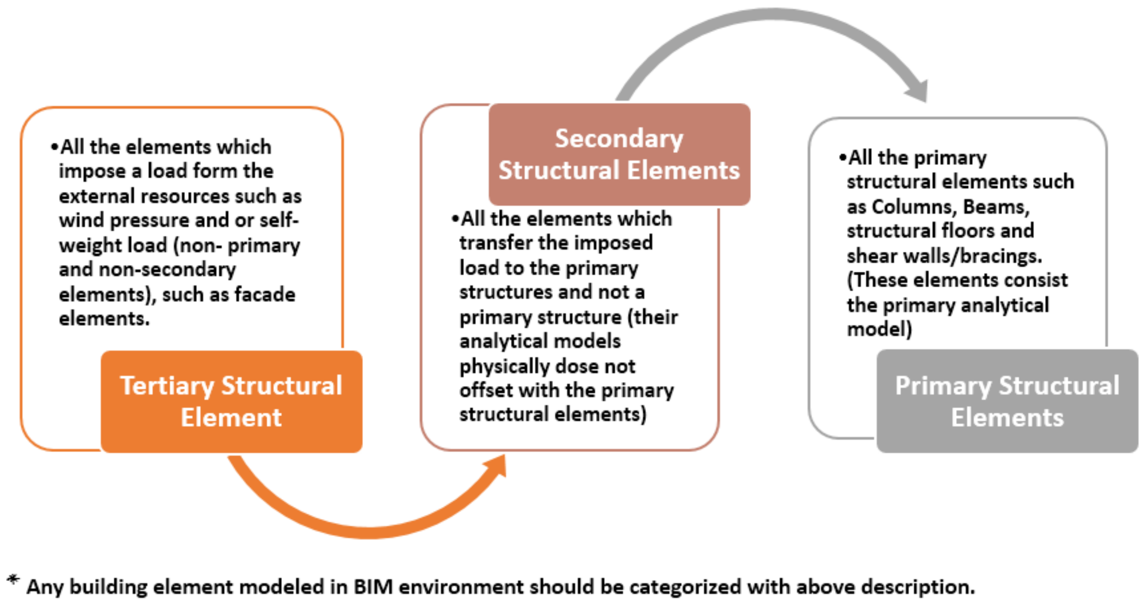

Fig. 5-8 Element Classification logic as per their participation in structural design and load applications

At this stage using the defined classification and reference planes, the software can extrapolate the location of each element while simultaneously merging the analytical model elements to allow for structural analysis in later steps. This process is illustrated in Fig. 5-9.

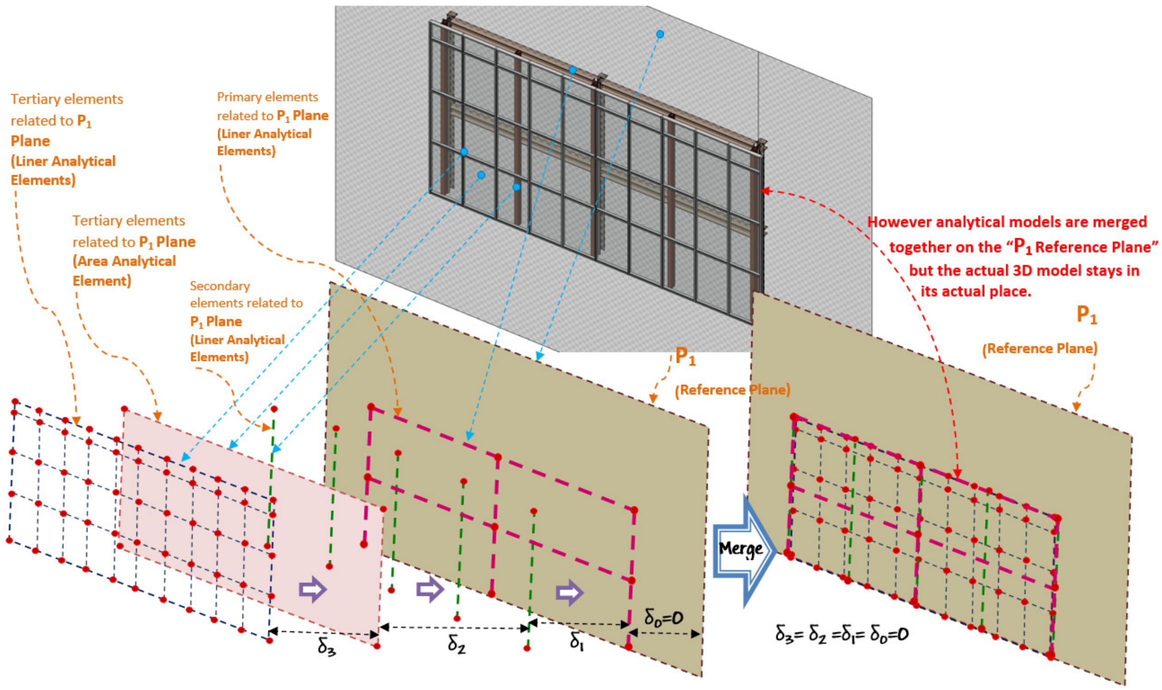

Fig. 5-9 Software prediction for model placement process

5.3.4.4 Geometrical load application/calculation and determination of the tributary area

Using the properly aligned analytical models with the inferred structural/mechanical relationships between the different components structural analyses can be run. Similar to the flow in the defined categorization for structural elements, calculated loads will be transferred from the tertiary elements to the primary elements through calculated load assignments. Fig. 5-10 illustrates this automated load calculation and application processes inside BIM design authoring tools.

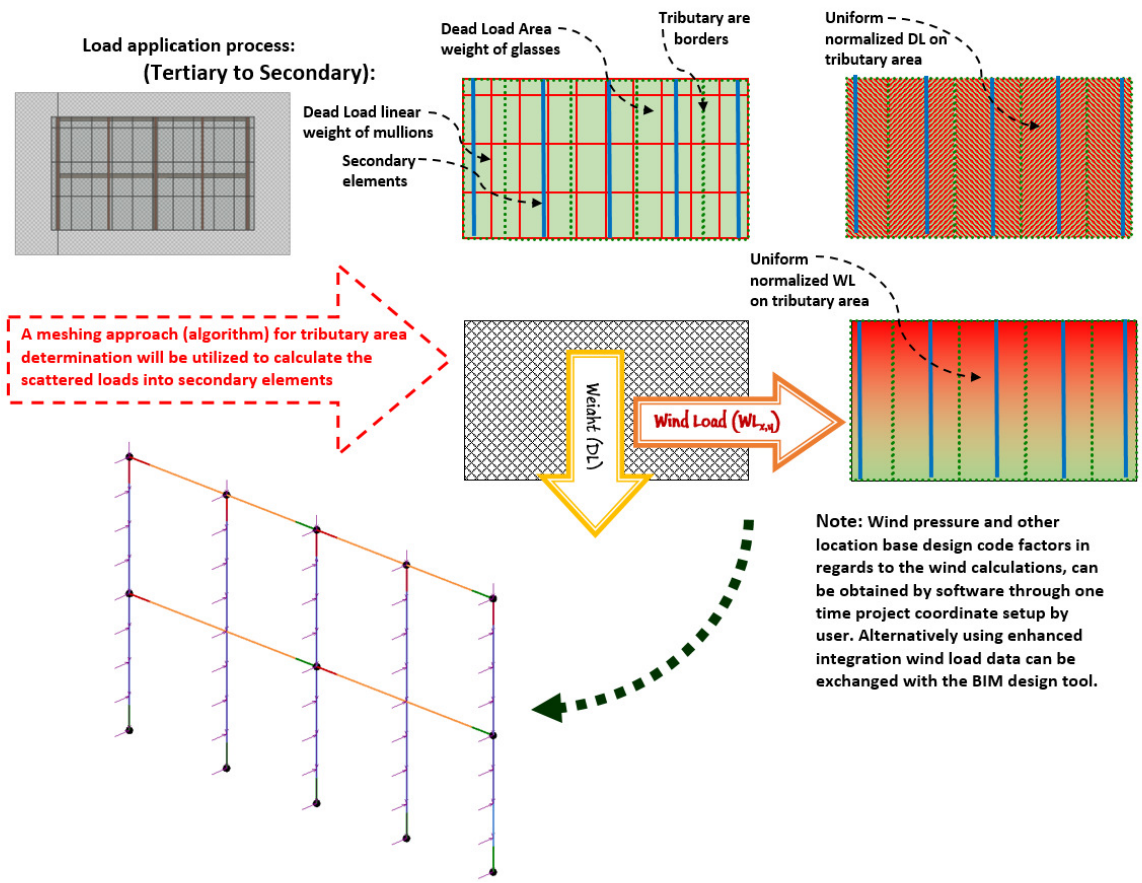

Fig. 5-10 Automated structural load calculation and application process

5.4 BIM process change and improvement of the existing BIM protocols

5.4.1 Adding shared parameters for user input in GUI

The implementation of the proposed Planar Concept for automating the use of structural analysis into the BIM process requires a few modifications to the traditional element family models. Elements require a classification and a referenced plane that is assigned to each element by the user through the software interface. New model element information attributes/parameters need to be created to capture this information. Fortunately, these parameters can easily be defined in most BIM design authoring tools across the project, for example using shared parameters in Autodesk Revit definitions[32] also accessible in Revit through the “Element Property Grids”.

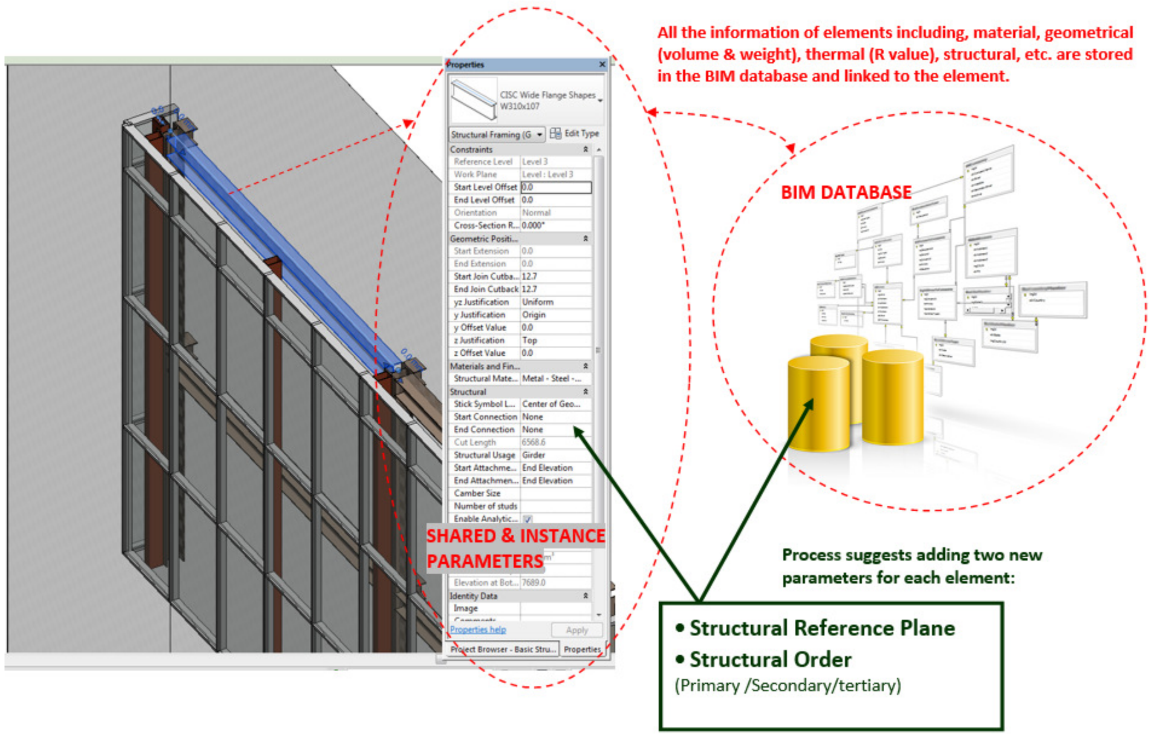

Fig. 5-11 Illustration of proposed changes in BIM design authoring GUI/Element Property Grid

5.4.2 Improvement for existing BIM standards/protocols

Currently, the CIMSteel Integration Standard CIS/2 defines a universal standard for transferring structural analytical models from BIM software to structural analysis/design software in order to maintain the consistency of steel member properties such as shapes (cross-sections), grades and geometrical aspects of the model. In other words, this data-exchange protocol delivers basic BIM interoperability in the structural steel industry[33].

An amendment to the CIS/2 standard is proposed (or other data-exchange standards such as IFC protocol) to define the accompanying load transfer strategies (i.e., dealing with units) for each element to maintain model completeness throughout the data exchange processes. Hence, the determined structural loads could also be transferred as the analytical models, for use after design. Fig. 5-12 illustrates the discussed process for structural loading transfer through improved BIM data exchange protocols. This new data exchange capability for load transfer could facilitate the automatic use of external structural analytical software, improving the efficiency and accuracy of structural design. This would require less manual effort and time, reduce the cost and duration of the design process while also increasing the earned value of the project.

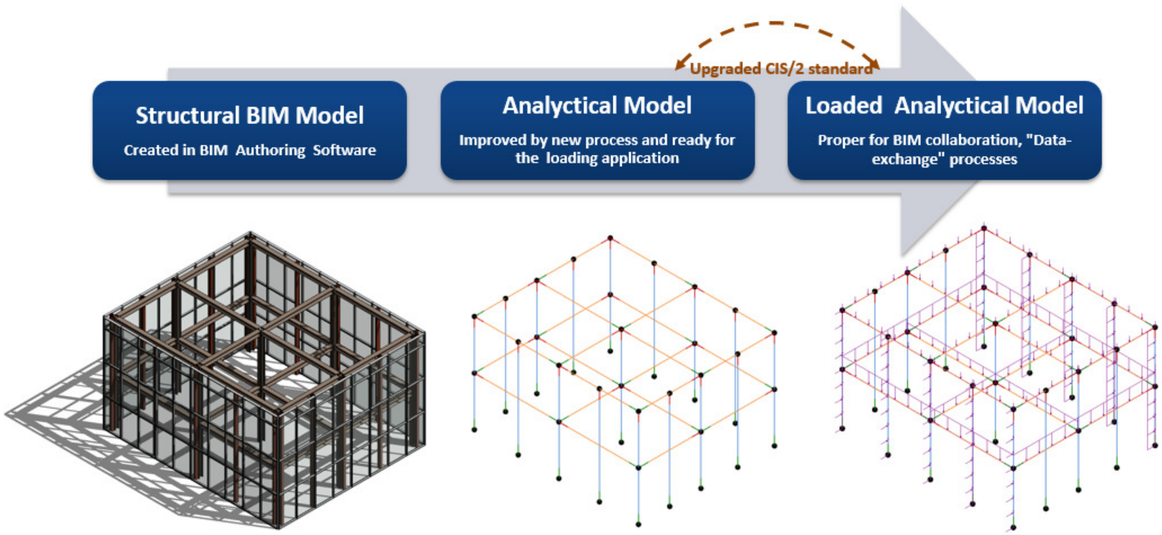

Fig. 5-12 Proposed improvement for BIM data exchange protocols such as CIS/2

5.5 Evaluation of the proposed concepts for automation in BIM Processes

To evaluate the feasibility and effectiveness of the proposed approaches, a software based on the Planar Concept and Floating LOD algorithm implementation was developed and evaluated. The developed PEB design tool uses the Autodesk Revit GUI to interact with users and Revit's underlying application programming interface (API). The tool automates the design and modeling processes of a PEB building. The PEB design tool performs architectural model development and structural analytical model development using pre-developed PEB structural and non-structural Autodesk parametric BIM objects (families) built for this application. The developed automation algorithms that incorporate the proposed concepts were coded and developed using Microsoft Visual Studio (.Net) using existing functions and libraries offered in Autodesk Revit Software Development Kit (SDK). The software command icons were added to Autodesk Revit as a separated "Ribbon". The sequence of tools used for software development, PEB design program interface on Revit GUI, added Ribbon and some output examples are shown in Fig. 3-10 (in chapter 3 of this thesis)

An example PEB project was used to evaluate the BIM framework, proposed concepts, and BIM automation implementation. The project was a real industrial PEB building that had been designed and developed using the traditional non-BIM system. The design of this 21m x 16m x (11.53m Eave Height) Gas Compression Station was originally done in the absence of any BIM model for PEB structures, the building enclosure, and a collaborative environment. As it is shown in Fig. 3-11, the building owner and general contractor developed comprehensive BIM models for all mechanical and electrical components of the building. Note that the rough 3D enclosure model that is shown in Fig. 3-11, is a low LOD CAD conceptual model developed by the owner to describe the required building and had no further value in later design steps.

Fig. 5-13 shows the classification defined for software that is recorded in the BIM database as a "Shared Parameter" through an element property grid. Fig. 5-13 also presents a schematic illustration of the defined referenced planes, the hypothetical plane where structural/analytical models are placed through the utilization of the Planar Concept for the Example PEB project.

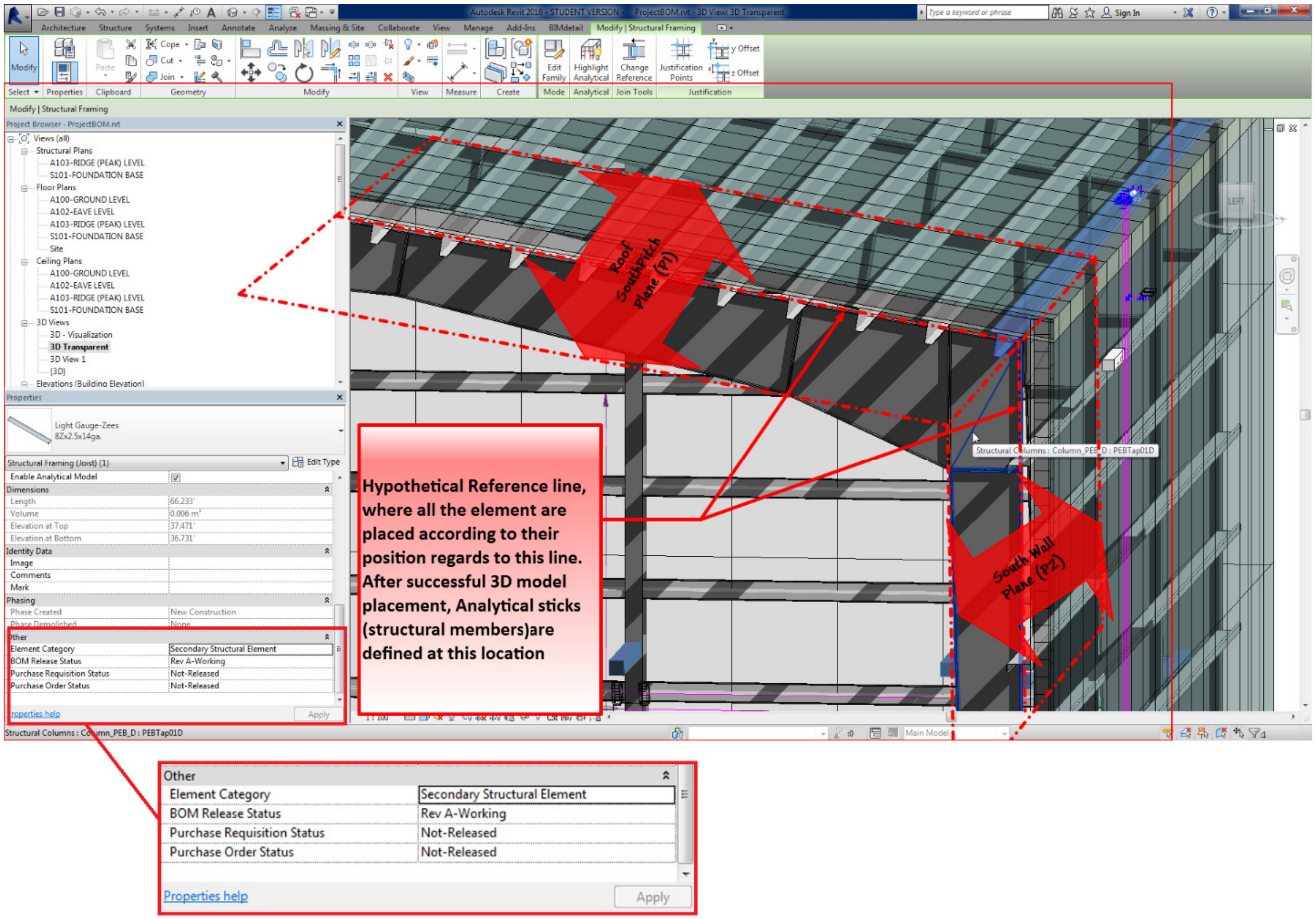

Fig. 5-13 Illustration of utilized Planar Concept (for automation purposes) and classification (Element Category) defined for software to create automated model development/placement processes

The user interface was designed to step through the BIM model development process (the steps and API interface are extensively discussed in reference [6]-chapter 3 of this thesis)). As a result, the PEB design software developed the BIM model to LOD300 automatically in minutes as compared to the hours it would take to perform this task manually. (referred to the example project report in reference [6]-chapter 3 of this thesis). Overall, the design development, modeling and design drafting of the project were reduced to a time of 4 hours instead the estimated 120 hours. (as required in a traditional BIM approach). Through the intelligence in the PEB family models, the software was able to place all the model elements accurately in their appropriate locations. In addition, the software used the user provided reference planes and the Planar Concept to determine the logical location for structural/analytical model elements.

It is worth mentioning that the different PEB model elements included intelligent placement algorithms that enabled the automated model development process to avoid clashes automatically. Through a collaborative (in the presence of mechanical/electrical BIM models) approach, the software placed the model elements in clear spaces and accommodated framings for the required opening around the clashing objects (see reference [6]-chapter 3 of this thesis).

Finally, at the end of the design generation process, the developed architectural and structural BIM models were ready to be transferred using the CIS/2 standard format. Fig. 5-14 presents the successful design.

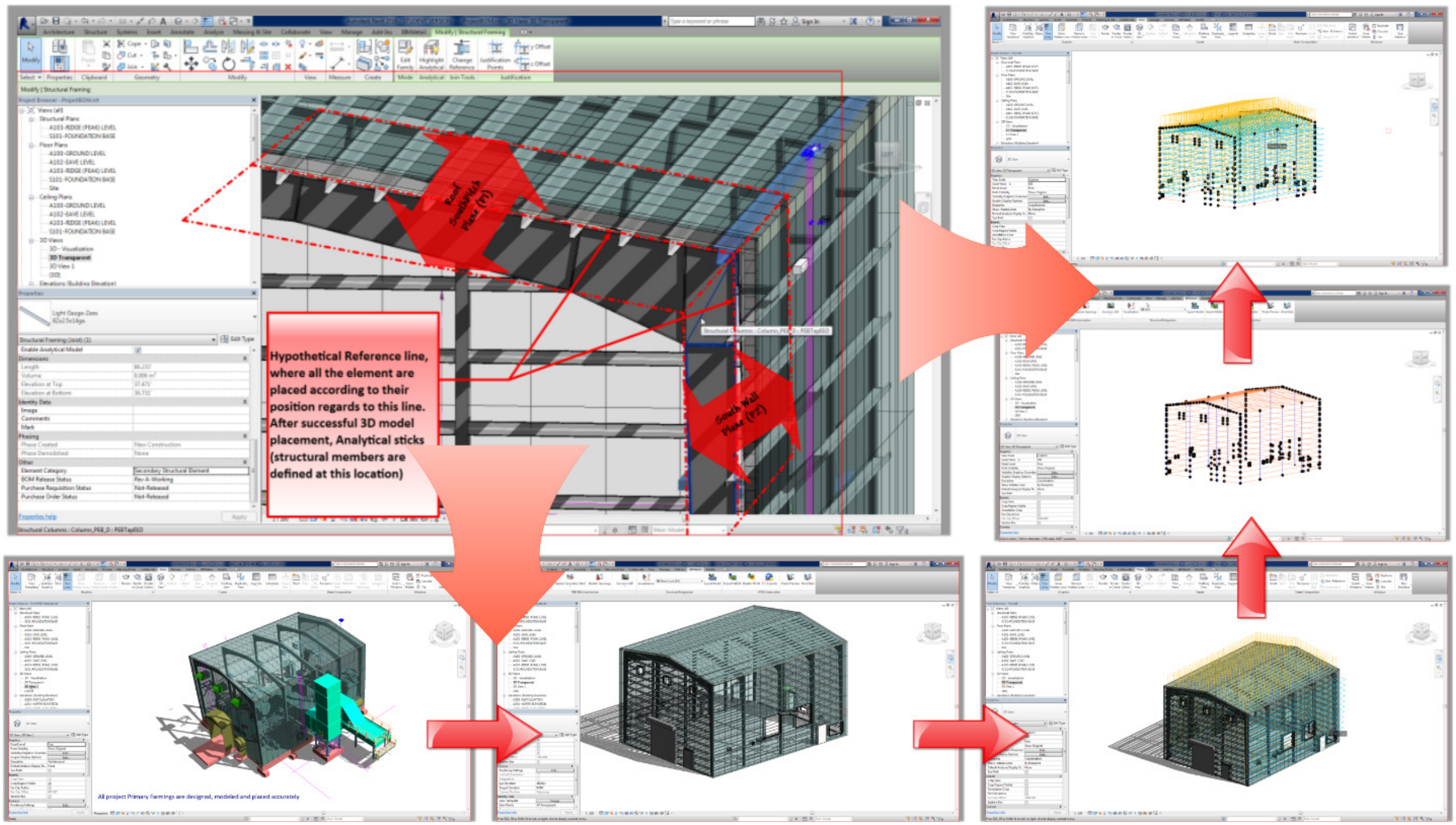

Fig. 5-14 Illustration of the automated model development processes and the results

5.6 Conclusion

Although the application of BIM can streamline project coordination, design collaboration, drafting, and design drawing creation, materials quantity take-off and project management activities of a project, it requires sufficient model development (higher LODs) to deliver these benefits. As manual modeling inefficiencies, can make it cost prohibitive to create sufficiently developed models, this paper focused on developing mechanisms to enable the automation of a part of the design development process.

The PEB industry was used as both a test domain, given its traditionally high use of design automation in its processes and a place to evaluate if BIM-based design automation was feasible, given its current lack of BIM adoption. The PEB approach for modeling and designing architectural and structural models simultaneously was adapted for automation and deployed in a BIM modeling environment. By classifying building elements to indicate if they had a structural role and by using intelligent building element models, the automated BIM software was able to shift the design model between LODs to support different uses without manual editing. This was introduced as the floating "LOD concept".

A "Planar Concept" was also introduced to provide a link between designed structural elements and analytical model elements to support the integrated structural analysis of designs as part of the process. The Planar Concept made use of more traditional drawing reference planes and the building element classification to realize the Planar Concept creation of the analytical structural models simultaneously with the development of the architectural model.

Fig. 20 illustrates further potential direct and indirect impacts of the mechanisms used to Planar Concept achieve automation in the BIM design process.

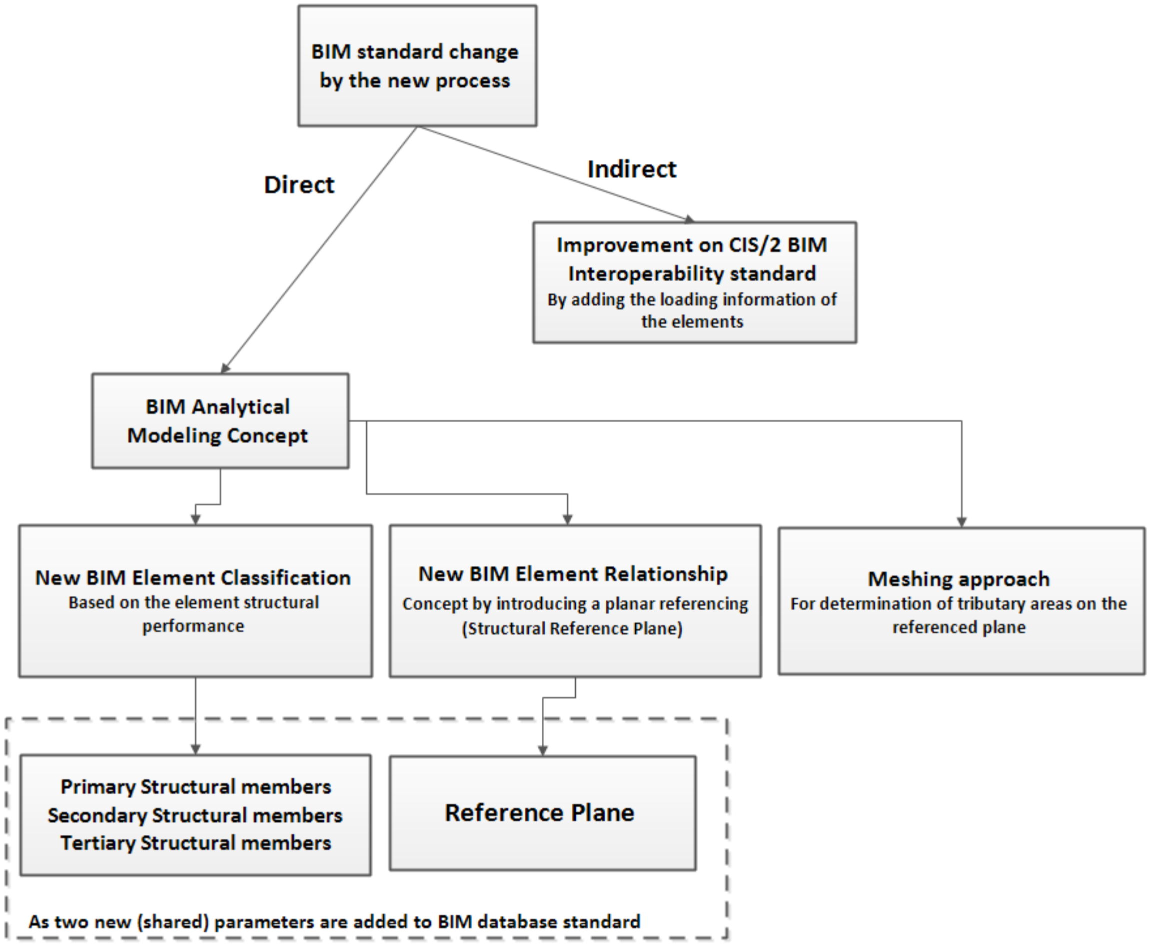

Fig. 5-15 - Further potential impacts of the mechanisms used to automate the BIM design and analysis processes.

As indicated in Fig. 20, the use of automation in BIM provides an opportunity to generate and exchange imposed/calculated loading for BIM structural analyses by extending existing data exchange processes. The required exchanges would need to include loading scenarios and added element classifications.

The successful creation of a reasonably complex example BIM model of PEB project Planar Concept using a software implementation illustrated the feasibility of the developed algorithms and proposed concepts. The example demonstrated that the automated design algorithms were able to generate and position elements to complete the development of the design as well as build the accompanying structural analysis model.

Acknowledgement

Natural Science and Engineering Research Council of Canada (NSERC) is gratefully acknowledged for the financial support to conduct this research project. Last but not the least; the authors would like to show their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was developed.

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Chapter 6

6 Automated BIM-based Process for Wind Engineering Design Collaboration

Abstract

Building Information Modeling (BIM) is a collaborative design process/system that can bring all project stakeholders in different disciplines to the same platform, to contribute to the design phase of a construction project. In this paper, the development of an automated BIM system to facilitate an integrated BIM system for structural design and Wind Engineering analysis is presented. The research was focused on Pre-Engineered Building (PEB) as a case study. This research proposes novel BIM concepts such as "Planar Concept" and "Floating Level of Development (LOD)" to facilitate the implementation of automation in the BIM model development processes. These concepts facilitate engineering analysis integration and overcome challenges associated with creating and working with different LOD models. The BIM integrated system collaborates with primarily computational aerodynamics assessment tools (but could also be useful for experimental approaches) during building design phase. The proposed system uses a central database and outputs a 3D model of the building and the computational domain for use by the computational fluid dynamics software. A BIM-based Application Program Interface (API) and a stand-alone software were developed to evaluate the proposed system and its feasibility. The results suggest a successful integration that could significantly improve the building design quality and further facilitate wind, or other, engineering design collaborations. It is also observed that the process could be applied to the general Architecture, Engineering, and Construction (AEC) industry.

Keywords: Building Information Modeling (BIM), BIM design collaboration, BIM Level of Development (LOD) Planar Concept, Floating LOD, BIM Engineering Integration, Wind Engineering, Pre-engineered buildings (PEB), metal buildings, cold-formed steel system,

6.1 Introduction

There is a growing use of BIM in the Architectural and Engineering and Construction (AEC) industry. This study focuses on BIM-based engineering design/analysis process integration for Wind Engineering in which an intelligent modeling software integrates design and analysis methods using the BIM model to produce design specifications. BIM interoperability can already be used to form the basis for passing on information to owners and operators for use in maintaining and operating their facility's systems. Other construction disciplines, such as energy analysis, structural analysis, etc. can also benefit in a similar fashion. Better access and use of these domain-specific analyses tools and performance simulations through improved interoperability can significantly improve the design of facilities and yield results such as reduced energy consumption during their lifecycles [1].

BIM-based information transfer and workflows also make it possible to automate analysis processes that can result in time and cost savings during design and analysis while delivering more accurate results. Some of the BIM software vendors (such as Autodesk, Nemetschek, Bentley) already offer integrated engineering analysis and design functionality packages as well as standalone BIM design authoring and BIM design review tools. The MacLeamy curve, shown in Fig. 6-1 illustrates how BIM engineering integration and collaborative design process can improve project design quality (MacLeamy 2004) [2]. The curve shows that the ability to impact cost and functional capabilities of a construction project decreases over time from design to operation phases. This reduction occurs while the cost of making design changes increases as a project gets closer to its operation phase. However, most of the project design (which could be presented as Architectural and Engineering design) is traditionally handled when a project has lost some of its flexibility for dealing with changes. Consequently, changes triggered by analysis results could become costlier. A number of different foreseen or unforeseen factors can cause construction project change orders such as design modification, errors, omissions, change in conditions, additional/reduced work scope, work sequencing, etc. [3]. According to the suggestion by MacLeamy, the preference is that an efficient design system could predict and react to probable design changes at the end of schematic design phase (mostly involving architects and owners) and at the design development phase (mostly involving architecture and engineering design disciplines). This preference is presented in the curve 4 in Fig. 6-1.

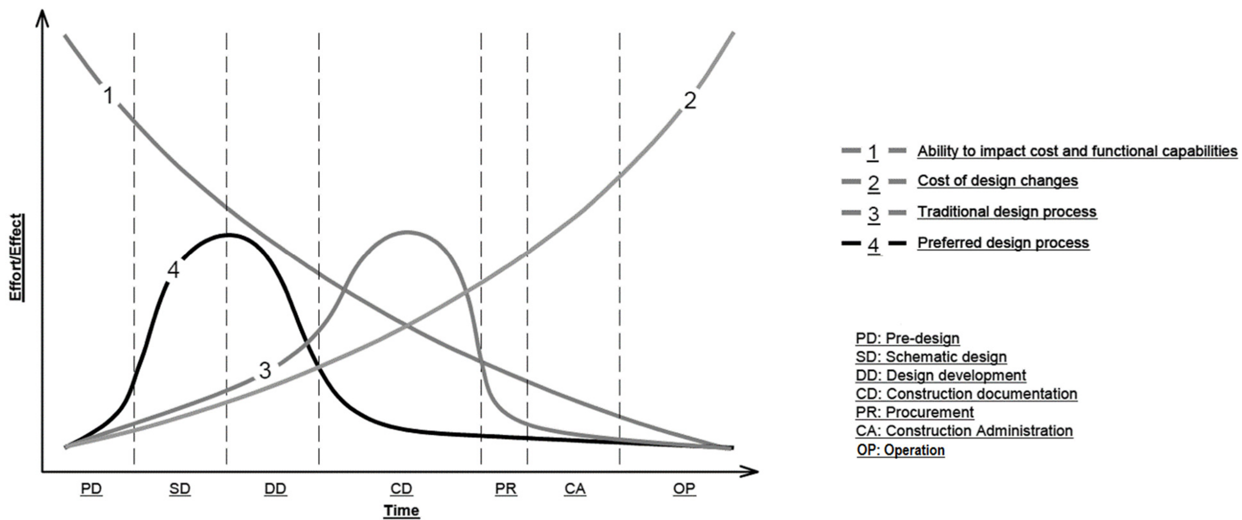

Fig. 6-1. MacLeamy curve on Effort/Effect Vs. Construction phases

Schematic Designs, when represented in BIM models can be considered as having lower Levels of Development (LOD). These low LOD models in a collaborative approach can be shared between owner, architect and engineering design parties. As per most of the BIM guidelines (i.e., "PennState BIM execution planning guide"), the shared BIM model should be the base source of design information for all stakeholders. As the project design progresses further, the models will be shared through model/data exchanges and developed by different stakeholders. Through this, the building design model will progressively have higher and higher LOD. Note that a project Model Element Table is normally created to clearly define all the different parties responsibilities for contributing to the model development.

This approach is most feasible for Integrated Project Delivery (IPD) method but is still achievable to different degrees within Design Bid (DB), and Design Bid Build (DBB) project procurement methods as well [4,5]. Based on the described processes and by addressing the MacLeamy curve, BIM can be substantially considered as a preferred design approach. Using BIM model exchanges; design modification, errors, and omissions change conditions can be predicted and covered by involving all design parties in the development of a shared model. Using BIM design review tools and the shared BIM model, issues, such as building component clashes and difficulties in engineering design, can be identified by all project stakeholders involved in the design process. Whenever cost and work sequencing is an issue for construction management team or owners/operators, BIM 4D, and 5D modeling can help predict and control the impact on the project schedules. Therefore, changes regarding the cost, scope and sequencing issues can also be addressed in the engineering design development processes [1,6,7]. Because of this BIM could improve specialized expertise and services offered by engineering design firms. In particular, it is possible to achieve optimal design solutions by applying various rigorous analyses through BIM interoperable software chain and realize faster Returns on Investment (ROI). In summary, BIM can improve the quality and reduce the cycle time of the design analyses .

In the SmartMarket Report -2012 by McGrow Hill Construction [8] BIM was surveyed to be implemented by at least 67% percent of engineers and engineering firms involved in construction contracts in North America. However, the report also indicates only a 37% ROI on BIM utilization for engineering design [8]. This lower rate of ROI outcome from BIM implementations by engineers indicates the absence of an effective integrated engineering design and analysis system. Many of the causes for this are technical and include challenges such as proper BIM LOD selection, interoperability, and data exchange issues.

The integration of BIM and engineering design processes for Wind Engineering, primaily focussing on pre-engineered buildings, is presented in this paper. This includes discussing some of the benefits and challenges of utilization of this integrated system. The proposed BIM-based integrated design system incorporates Wind Engineering processes into the building design phase, using a central database and by using an automatically created 3D model of the building and computational domain to be utilized by the computational fluid dynamics (wind engineering) module. A BIM-based API and a stand-alone software were developed by authors to evaluate the proposed system and its feasibility.

6.2 BIM integration with Engineering Analysis/Design

There are both technical and non-technical challenges in the deployment of BIM in engineering design processes for the pre-engineered building industry (an industry that is mostly involved in the project design process as structural engineering party). Non-technical challenges are encountered due to the paradigm shift in the design process and tools for engineers (and engineering firms) utilizing the traditional CAD or non-BIM design systems. Also, engineering firms are understandably hesitant to transfer high LOD BIM models due to risks regarding the intellectual property of the designs (reserved for fabrication) and new liabilities arising from potential inaccuracies in exchanged models ([9]-Chapter 2 of this thesis). Challenges on the technology side include the youthfulness of the sector and its software tools and unbalanced development and differences in communicating languages between software makers platforms [10]. Despite the remarkable efforts by international BIM organizations such as buildingSMART [11], for standardizing the BIM processes and input/output formats, many BIM systems still suffer from such interoperability issues. In a similar way, engineering firms face two deficiencies, namely; lack of technological development and interoperability issues regarding the BIM integration with engineering processes [6,12]. As explained using the MacLeamy curve, BIM model interoperability and transfer is core to creating the desired collaborative and flexible design process. Other types of technical issues with existing BIM technology include difficulties with the model development processes and LOD issues (i.e. defining an optimum LOD and the effort required to develop the model to the defined LOD target) [9] (See Chapter 4).

Fig. 4-4 illustrates the suggested automated and non-automated BIM system and highlights the traditional BIM model development. The traditional, dominantly manual, method of model development can become time-consuming and costly for AEC industry, especially when engineering analysis using BIM integration are expected as a regular part of development. Complicating this is the fact that overly detailed models, with higher LODs, are required for some types of analysis, such as cost analysis, where alternate and often simpler derivative analytical models are required for engineering analysis. Managing the LOD of the models and picking optimal levels for LOD and developing automated processes to reach to that level are thus important challenges for an efficient BIM-based engineering design and analysis process ([9]-Chapter 4 of this thesis)

This paper proposes some resolutions for these existing barriers to successful BIM implementation in AEC industry and uses a Pre-Engineered Building (PEB) project as a case study. It is worth noting that the results of this work can be applied beyond the case study to the general AEC industry. The work here relies on earlier work by the authors that introduce two concepts, the “Planar Concept” and “Floating LOD”, to support the implementation of automation in the BIM model development processes ([9] -Chapter 5 of this thesis). This work makes integrating engineering analysis and managing related LOD selection challenges manageable. Through these concepts, an example application using BIM to integrate structural design and wind engineering analysis are presented.

As illustrated in **Error! Reference source not found.**, the general objective for automating the process in this research was to reduce the time required for a BIM model to be developed to a required LOD for the model element positions and associated information. The results of the earlier research done by [9] (see -Chapter 4) had determined that LOD300, as described in AIA’s G202 document and NYC’s guideline specifications[13,14], was identified as an ideal LOD due to its balance of utility/value of the BIM models and the resources invested in developing them. As such, LOD300 would thus be an appropriate initial target output for any automated design process. The input for the development process could be any lower LOD.

The earlier work ([9] Chapter 4 of this thesis) also proposed a concept called “Floating LOD” to deal with cases where different LOD requirements arise for different uses of a BIM model. In short, this “Floating LOD” concept proposes allowing reversible automated design processes to raise a model’s LOD where required and the designer to lower it if needed. This approach can be described as a generalization of utilizing BIM attributes and parametric families which are not just limited to building sub-components (i.e., doors, windows, kitchen utilities), but also to main components (system families by Autodesk’s Definition[15]). Further discussion of this “Floating LOD” can be obtained in ([9] Chapter 4 of this thesis)

Another newly developed concept as part of the current work in larger context is the "Planar Concept". This concept describes how grouping and categorizing similar elements in BIM design could help the automation of the design process. In particular, many design elements will have, usually simplified, non-physical/analytical analogs that are used in engineering analyses that should be grouped or categorized with their physical design equivalents. Unfortunately, the positioning of the design elements and their non-physical analogs cannot be defined easily using the same frames of reference. In general, the position of 3D design elements in design environments is described by referencing some snap points around their geometry. Non-physical elements are typically represented by line segments, planes or points (e.g. in structural analysis models) and thus lack 3D geometry and the associated snap points. If this is not properly accounted for, any analysis models derived from these groupings of elements are unlikely to represent the design scenario effectively. This could undermine any efforts at integrating analysis into the automated PEB design development processes. The "Planar Concept" relies on introducing building elements in three different classifications, regarding their application as shown in Fig. 6-2. The logic of the element classification is based on their relative location to the primary structural element. This logic is also aligned with any structural or thermal load transfer to the building through façade elements (an engineering design concept).

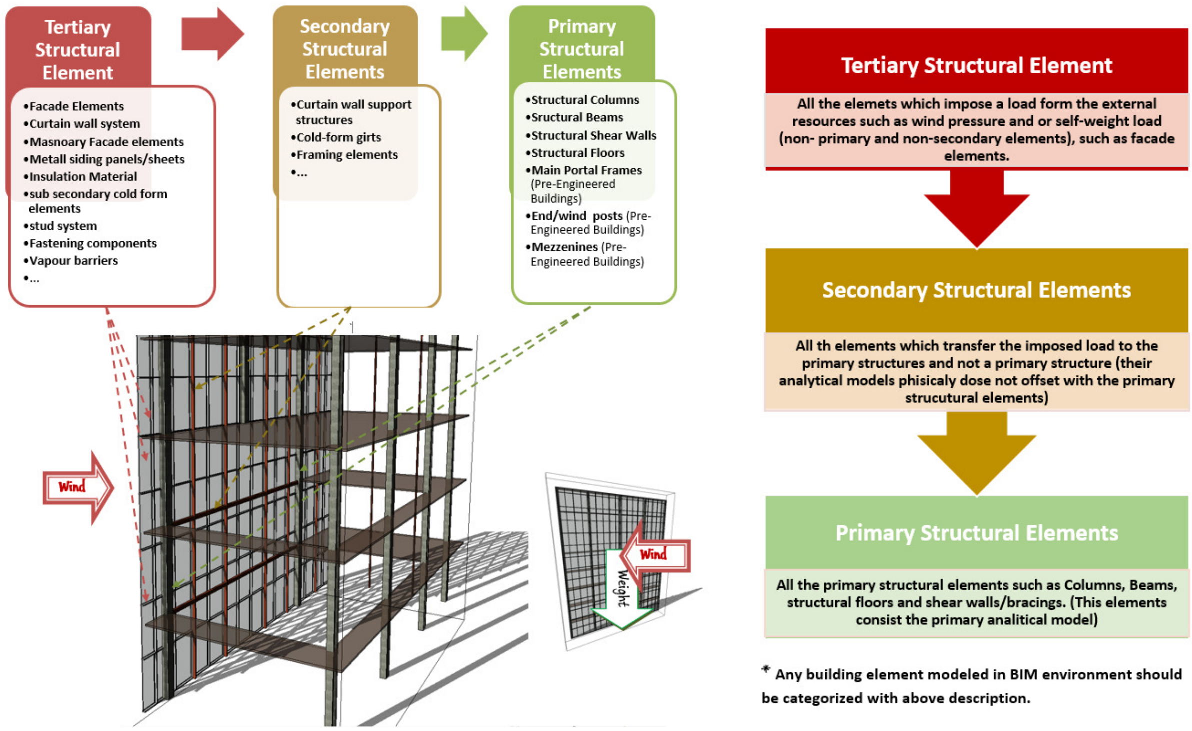

Fig. 6-2 New BIM element classifications suggested in Planar Concept for automating the BIM processes. Illustration of an example conceptual BIM model. ([9] -Chapter 5)

The Planar Concept references the model placements of all the physical and non-physical sub-elements to a unique reference plane. Traditionally, in BIM design development, reference planes are BIM element placement helpers for precisely locating elements in a 3D environment using a 2D perspective. Fig. 6-3 illustrates how all the building elements in an example BIM model can be assigned to a unique reference plane.

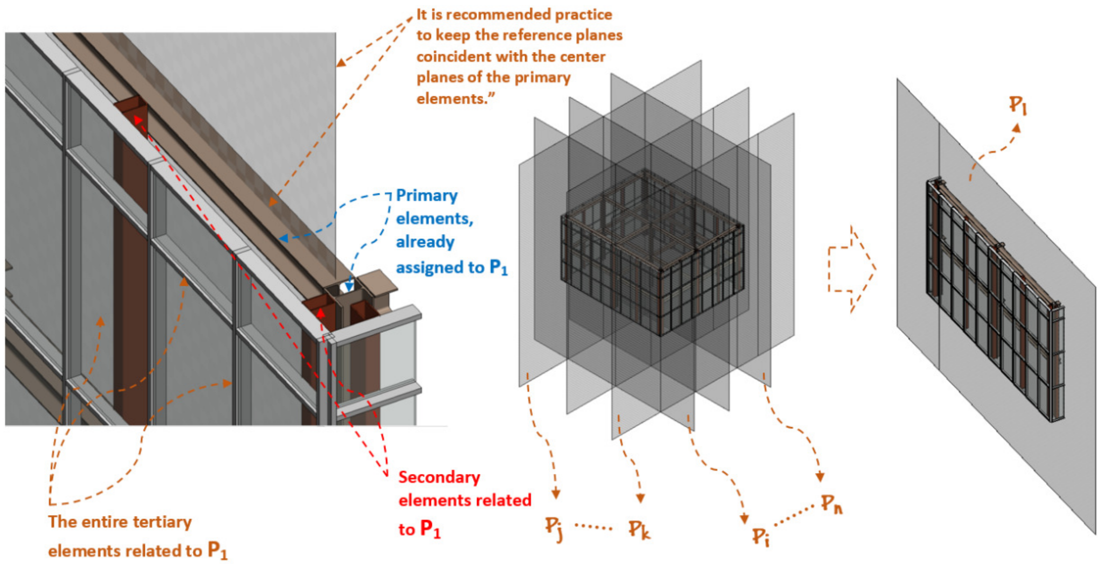

Fig. 6-3 Illustration of the assigned elements to a unique reference plane (P1) on an example conceptual BIM model

Using the defined classifications and reference planes, the software is supposed to calculate the location for placement of each analytical element (Fig. 6-4) relative to its design element while it merges duplicated analytical elements to keep the analytical structural model consistent for later analysis steps.

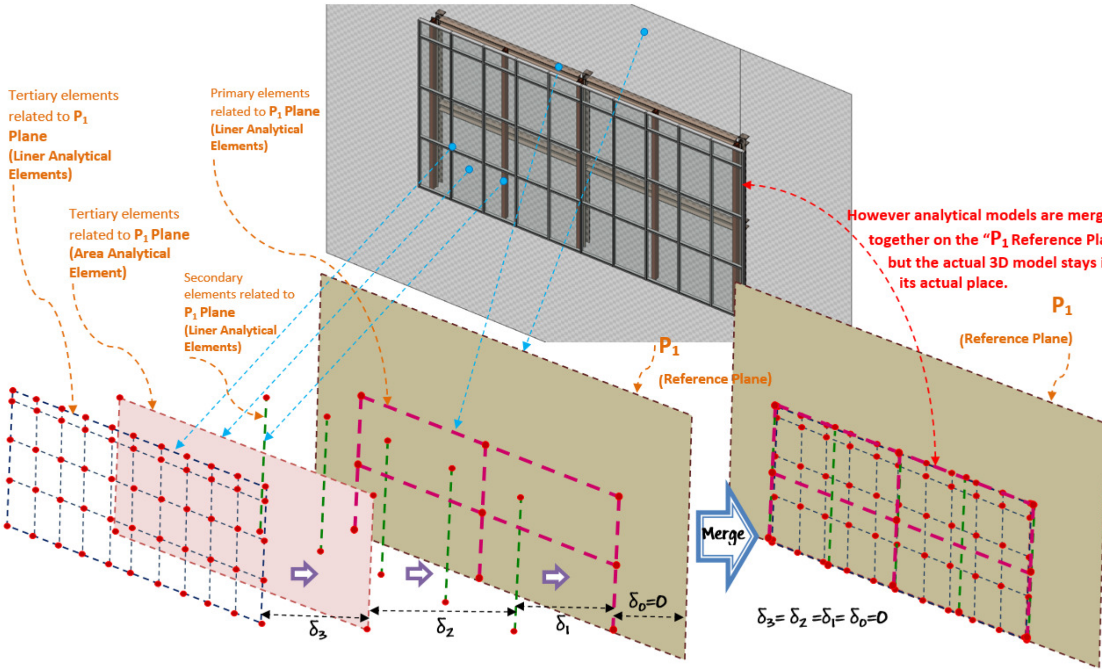

Fig. 6-4 Software calculations for analytical model element placement. Illustration of integrated (architectural and structural) BIM modeling developed by Planar Concept

This process was introduced by the Planar Concept to create an integrated (architectural and structural) automated model development process. As it is shown in Fig. 6-4 using the defined logical relationship (element classification) errors and discrepancies in the structural model can be eliminated (Fig. 6-5)

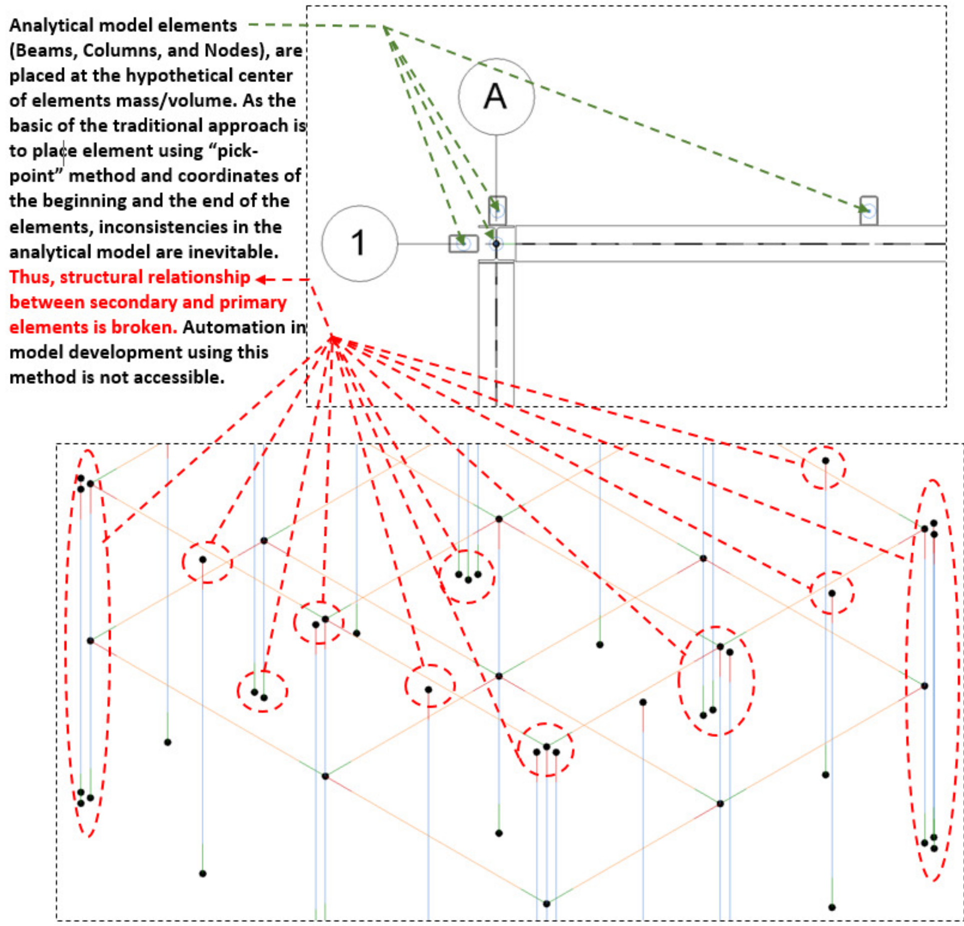

Fig. 6-5 Errors and discrepancies in the analytical model due to standard BIM modeling entity placement frames of reference (Primary and Secondary Structural Elements)

6.3 BIM and Wind Engineering

Wind engineering is a specialization that draws upon meteorology, fluid and solid mechanics, architecture, structural dynamics, and environmental science. The tools used include atmospheric models, atmospheric boundary layer wind tunnels, large open jet facilities and computational fluid dynamics based numerical models [16,17]. For selected shapes of buildings and cases, building codes and standards prescribe analytical or tabular methods [18,19]. Over the past decade, some efforts have been made to integrate BIM, structural, mechanical and electrical engineering. The development BIM engineering software packages offered by major BIM software such as Autodesk [20–22], is evidence of such efforts. In contrast, wind engineering integration is lacking properly defined engineering collaboration processes, related technology development and required integrated BIM-based software. This integration is particularly important as the responses, or target design parameters are dependent on the shape of the study building, openings, cladding layers, etc. that are captured in the BIM model.

The wind loads and appropriate load factors that allow the design of ordinary buildings are often prescribed by the analytical methods given in building codes [18,19]. For complex situations or cases not prescribed in building codes and standards, wind tunnel based investigations or complex fluid-structure interaction simulations can be conducted. A project-by-project wind load evaluation using boundary layer wind tunnel testing is an industry wide accepted procedure. Alternatively, the application of Computational Fluid Dynamics (CFD), particularly in wind assessment and building science is fairly new but is quickly becoming mature [23] and has wider design application implications. For example, the use of computational approaches now makes it feasible to seek optimal designs for the building shapes resisting the wind load [24] and generate more accurate building thermal performance assessments [25]. Integrating this with broadly used BIM-based design environments will allow for the further practical application of climate responsive design optimization, whether from safety or energy performance perspectives. However, in the case of Wind Engineering, one main obstacle is the lack software integration from design with appropriate CFD simulation tools. This lack exists in both the industry toolset and present academic literature.

The wind engineering process, either using experimental or high-performance computing, can be focused on sustainable designs (such as energy efficiency of buildings) or on enhancing the resilience of the design during hurricane or other extreme wind events. Developing the necessary processes and interoperability basis for integration of BIM with wind engineering and simulation will benefit both application areas. Fig. 6-6 illustrates the proposed process map and data exchange strategy for BIM integration with wind engineering. The illustrated process is discussed separately based on the simulation approaches (i.e. experimental or computational) in the following sections.

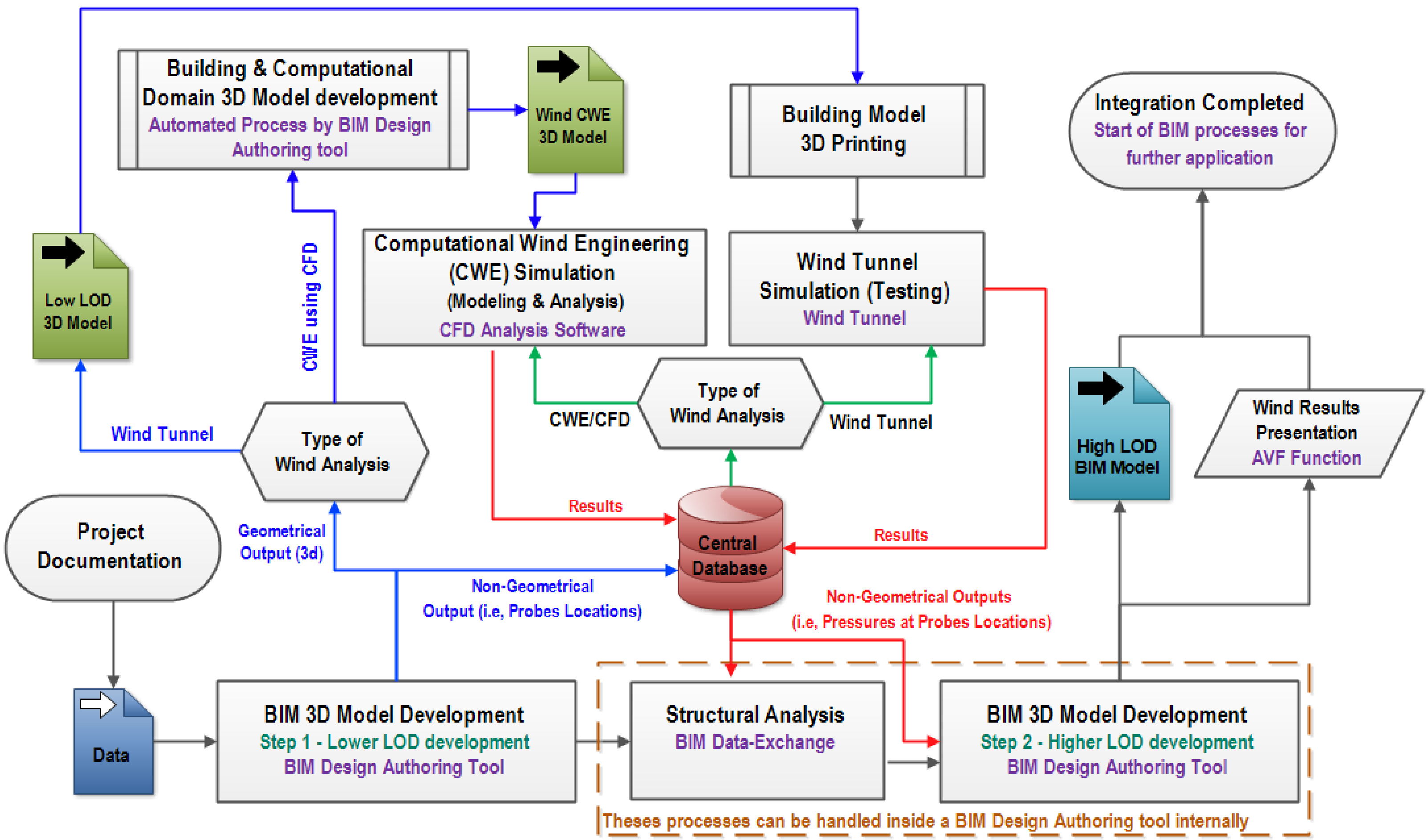

Fig. 6-6 Detailed process-map/workflow defining the 3D models/data exchange strategies and the application of the "central database" in BIM and Wind Engineering integration (For both Wind Tunnel and CFD based approaches)

6.3.1 BIM design integration with Wind Tunnel aerodynamic data analysis

Both wind simulation approaches, wind tunnel, and CFD deal with the significant amount of input and output data transfer, but wind tunnel approaches require more human intervention as it is based on applying a physical testing procedure. Wind pressure measurement points (taps) and associated aerodynamic data can be linked to the BIM model through a shared database as illustrated in Fig. 6-6. Ideally, this transferred data could be made directly available in the BIM design authoring tool. However, monitoring and management of the data could be a significant challenge given a large amount of data to be transferred. For example, for the simplest single solar panel test, the size of the pressure time history data for only 40 probes over a 30 second period in 0.0025-second fraction could be as big as 12000x40. Sstatistical parameters such as mean, max, min, standard deviation, peak, spectra, etc. on the raw data will also need to be displayed visually to the designer. To provide the engineer with access to this data during design, a stand-alone software supporting BIM design authoring was coded and developed. The Wind Engineering Data Analysis tool (WEDA) allows visualization and analysis on the main shared "Central Database" of the transferred CFD data to support the BIM design activities. This stand-alone software was developed using Microsoft Visual Studio and was connected to a shared central Microsoft Access database. User input panels were designed for specification of wind model and data transfer in the tool. To provide BIM modeling capabilities, the tool uses the Autodesk Revit (BIM design authoring tool) Software Development Kit (SDK) API and its built-in functions for manipulating the BIM models and creating automated processes. This tool can operate either as a stand-alone software that can access data without having a BIM tool or be accessed as part of the BIM design authoring environment.

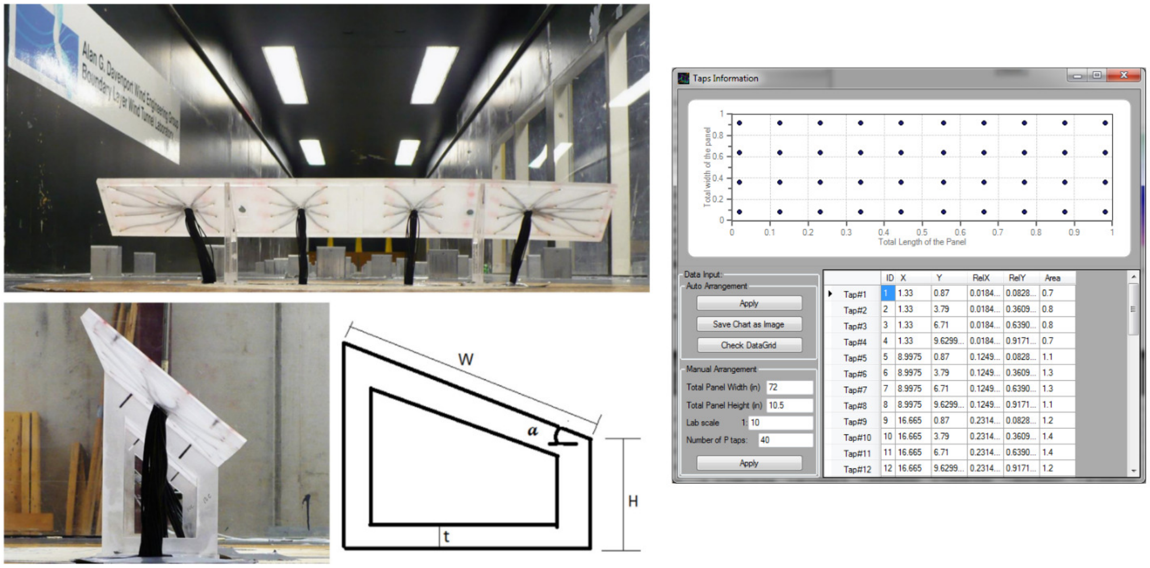

Fig. 6-7 The evaluation of standalone BIM portal software using the wind tunnel results of a test on solar panels[26]. WEDA Software interfaces for defining the data reporting point for BIM software and wind tunnel results.

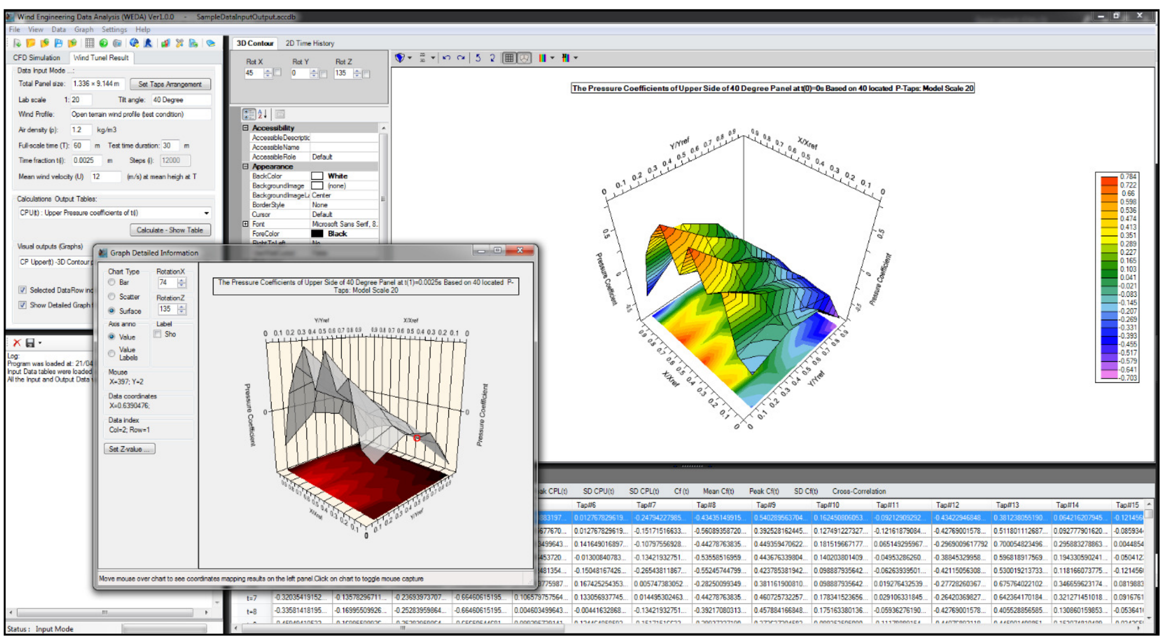

Fig. 6-8 WEDA interface for data exchange visualization and analysis. Example shows Pressure Coefficient of Upper Side (Cp) for solar panel with 40 Degree angle at t=0

WEDA tool was assessed using an example wind tunnel test on a solar panel conducted by Aly and Bitsuamlak[26]. As mentioned earlier, the key point in successful data exchange process is keeping the same referencing point (probes – pressure tabs location) between the BIM design authoring tool and output results; Fig. 6-7 illustrates the definition of these points using the software interface. The main stand-alone software interface is shown in Fig. 6-8.

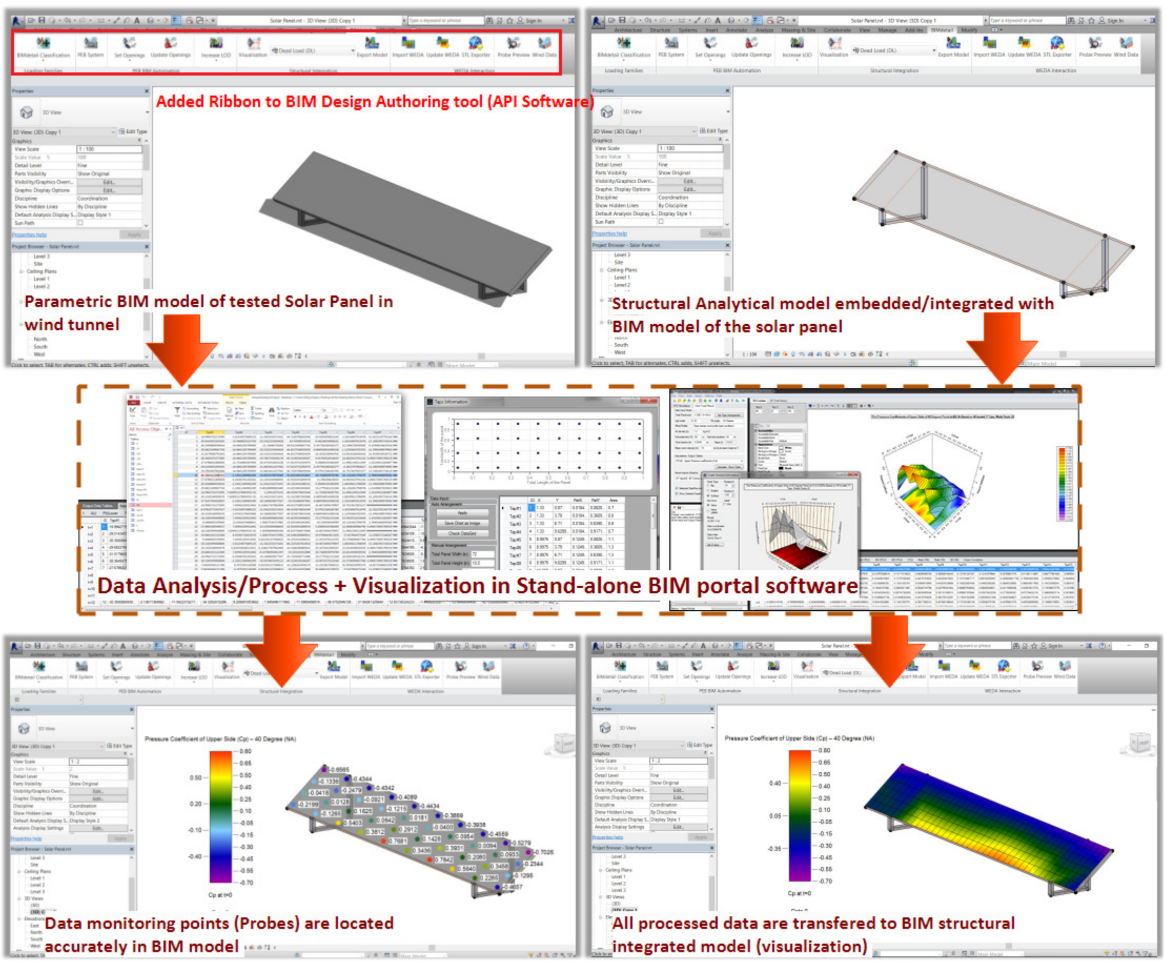

Fig. 6-9 The process of loading/importing evaluated and processed wind data from central database to BIM design authoring software using the developed API - Example shows Pressure Coefficient of Upper Side (Cp) for solar panel with 40 Degree angle at t=0 (t is the time-history steps which the wind tunnel results were recorded upon)

After evaluating the obtained data from wind tunnel simulation and processing, the raw and processed data are saved in the main central database. WEDA can import and load the data from the central database and present them on the superimposed on the BIM model for visualization proposes. Wind pressure and loading information obtained by wind tunnel testing also can be transferred to BIM structural integrated model using defined data monitoring points (probes). The process for data-exchange is illustrated in Fig. 6-9. It is worth mentioning that currently the 3D geometry of the BIM models are used for 3D printing of prototype scaled models for wind tunnel testing. Therefore the activity of creating the wind tunnel model is also included in the integration process map presented in Fig. 6-6.

6.3.2 BIM integration with computational wind engineering

The evolution of computational wind engineering (CWE) based on computational fluid dynamics (CFD) is making a numerical evaluation of wind effects on the built environment a potentially attractive proposition. This is particularly true in light of the positive trends in hardware and software technology, as well as in numerical modeling[27]. Significant progress has been made in the application of CWE to the evaluation of wind loads on buildings. Working groups have been established to investigate the practical applicability of CWE and develop recommendations for its use for in wind resistant design of buildings and for assessing pedestrian level wind, within the framework of both the Architectural Institute of Japan (AIJ) and European Cooperation in Science and Technology (COST) (Bitsuamlak & Simiu 2010; Dagnew and Bitsuamlak 2013).

The main task in integrating CFD and BIM is facilitating the transfer of various aerodynamic states (i.e. 3D building models with or without material properties). Depending on the target numerical simulation, communication between BIM, as a 3D model representation, and CWE, as a fluid/structure or heat transfer simulation, may entail only exchanging 3D models with or without material properties. The work here shows it is possible to automate this transfer. As an example case, the same “Solar Panel” scenario tested by Aly and Bitsuamlak[26], was chosen to be simulated through CWE processes. The goal was to demonstrate the process that was developed could handle both wind tunnel and CFD simulation approaches. The same process for defining probes in the CFD simulation software (CD-ADAPCO StarCCM+ Version 11.0[28]) was used to establish matching probe locations (and accordingly to obtain results out of the simulation analysis) in the BIM model through the central database. Also, to test how a proposed enhancement for automated scenario modeling could perform, a separate interface in the stand-alone software was developed. This interface allows the user to input a limited set of basic design parameters for a parametric family of elements from which the 3D BIM models are automatically generated in smart design authoring tools like Autodesk Revit. The interface is shown in Fig. 6-10.

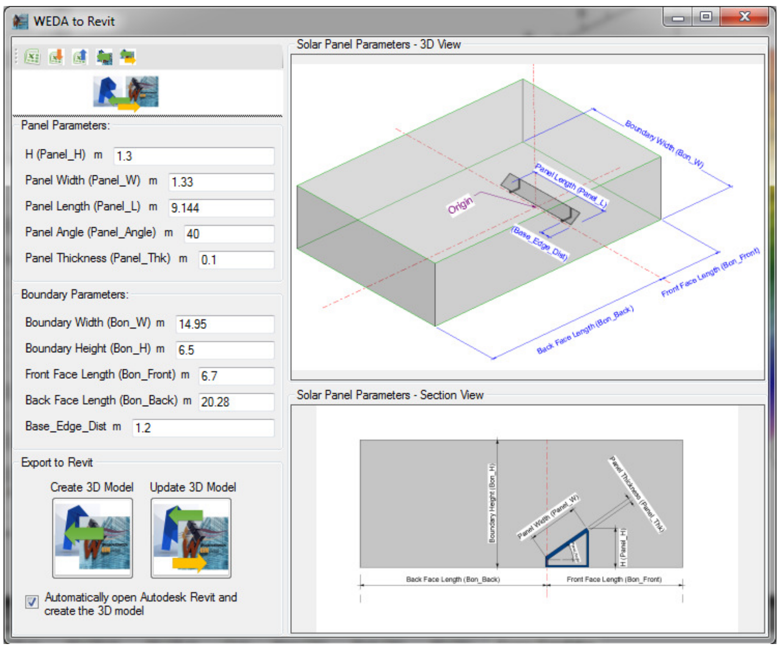

Fig. 6-10 Developed software interface for creating automation in 3D model development for CWE simulation using BIM environment on the solar panel case study.

Once the BIM design model is created, it needs to be shared with the CFD simulation software. Using built-in BIM modeling API functionality, the ability to create readable "STL" 3D solid models was developed. During the conversion process, the API finds all the CAD base 3D geometries (Solids) inside the BIM tool and polygonizes them to create the STL models. An STL ("StereoLithography") file is a triangular facetted or tessellated representation of a 3-dimensional surface geometry bounding a volume of space, the solid. Each facet is described by a perpendicular direction and three points representing the vertices (corners) of the triangle[29]. The STL files can be imported and loaded into CFD simulation software where they get segmented for defining the "Boundary Conditions" and wind resisting faces[30]. All the pressure monitoring points (probes) are defined automatically using the database for CFD simulation software (using a Java macro) and the results of the simulation are reported in a spreadsheet ".csv" format which is converted to MS Access ".accdb" tables to be used for further analysis in stand-alone software or for exchange with BIM API for further application. Fig. 6-6 provides a process map showing the different workflows and processes. Fig. 6-11 illustrates the different software platforms and interfaces that were used to deliver an integrated BIM design and CWE simulation of the solar panel case study.

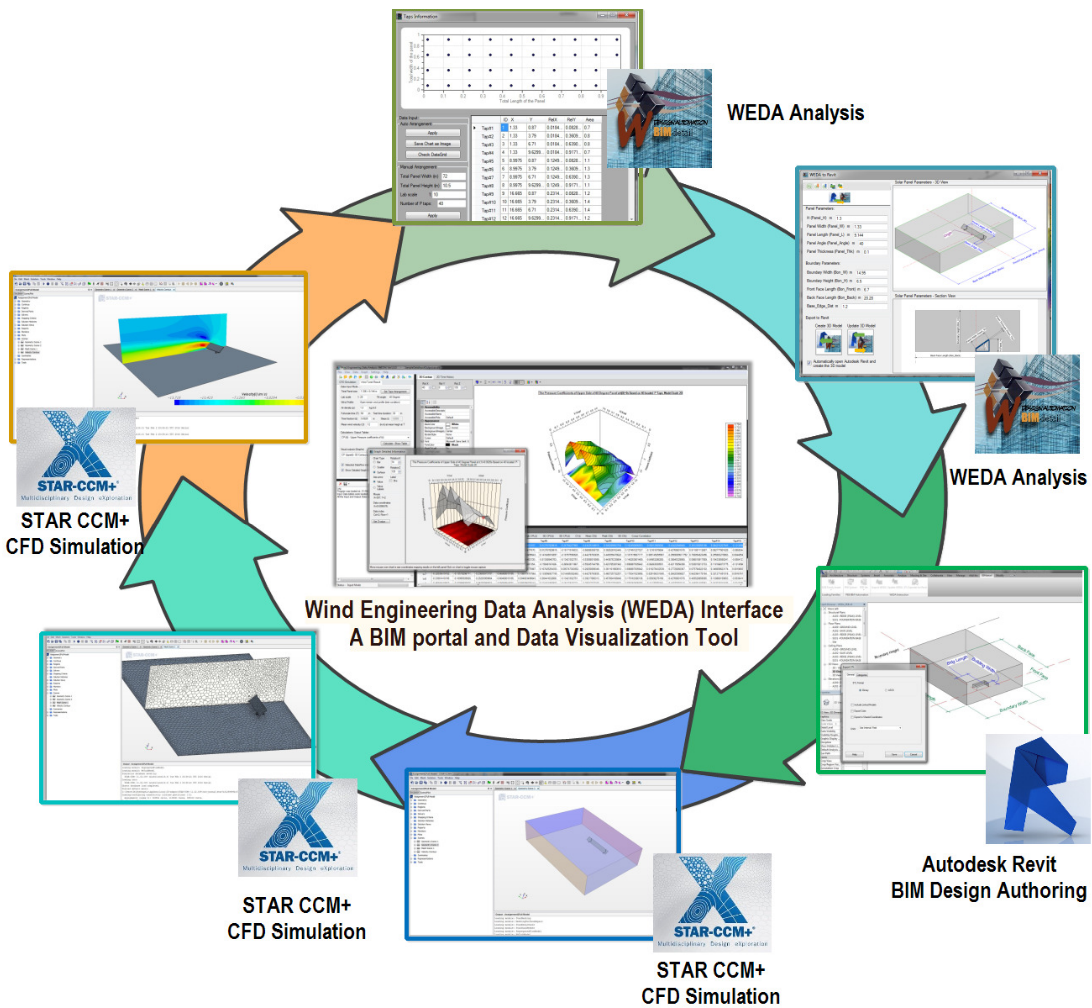

Fig. 6-11 The automated cycle of model 3D model creation for CFD simulator software using BIM design authoring tool and through the stand-alone BIM portal software

Using a parametric 3D BIM model and facilitated data transfer approach using the Central Database, the solar panel case study was modeled in different model-prototype scale (in this case to be compared with the wind tunnel results) and automatically processed through CWE software. The examination of the solar panel case was successful regarding the evaluation of the developed workflow and model exchange strategies, but the BIM process itself was lacking proper automation for generalized building model development uses. Although the process of creating 3D (STL) models from BIM model and data-exchange were automated, the automation process could be undermined when parametric 3D BIM models are not available. In real case scenarios (such as PEB buildings as the main case study in this paper) creating a parametric model of the whole building is not feasible. Also, having any parametric 3D model beside the actual BIM model of a building would be redundant and time-consuming in development. Since the core of the design process is the BIM model (and it is constantly exposed to changes), any automated design or analysis activities requiring alternate model representations requires that model to be generated from the main/actual BIM model of the project. For CWE applications where the structural resilience of a building is to be assessed, the authors used the Planar Concept introduced earlier in Section 2. (see also [9] -Chapter 5) to help generate the necessary analytical model.

6.3.3 From Planar Concept to CWE 3D model

Three main problems to be solved to create a fully automated and integrated BIM and CWE system are presented in Table 6-1.

Table 6-1 Three main targets to be achieved for creating BIM and CWE integration (problems to be solved)

Targets	Description
a)	To find an approach for creating a 3D model of the building and the wind computational domain automatically from the BIM model.
b)	To define an intelligent process that locates the probes on the 3D geometry surfaces/facades while keeping them (tangentially) orientated to the surface.
c)	To define a data representation and process that allows this information to be transferred between the BIM application and the CFD application. In particular, to be able to transfer any determined wind loads back to the BIM model for structural analysis. for

To solve the problems a) to c), the Planar Concept for 3D wind model creation is utilized. In Fig. 5 the logic of keeping consistency in the structural/analytical model by locating all the analytical representatives in planar location (reference plane) was explained. Therefore, the location of representative analytical models of BIM model components (which are classified in three categories) in 3D space can be independent of the actual location of those BIM model 3D components. Hence, the problem (a) and (b) would be solved if the wind 3D geometry could somehow be modeled exactly at the tangent of the referenced planes. Therefore, any defined probe location could be on the same plane with the structural/analytical representative elements, and load transfer matters could be automatically done. Alternatively, the problem (a) could be easily solved using an algorithm to create 3D surfaces (polygons/meshing segments) from the coordinate of the corners of a shape that is created by mirroring 2D footprints of all the 3D components belonging to the reference plane. This shape is created by mirroring the corners of the model element components belonging to the reference plane, as the reference planes themselves have no border. Fig. 6-12 illustrates the process for creating an integrated automated process for BIM and CWE modeling. The evaluation of the proposed concept and process done through an example PEB project is provided in Section 4.

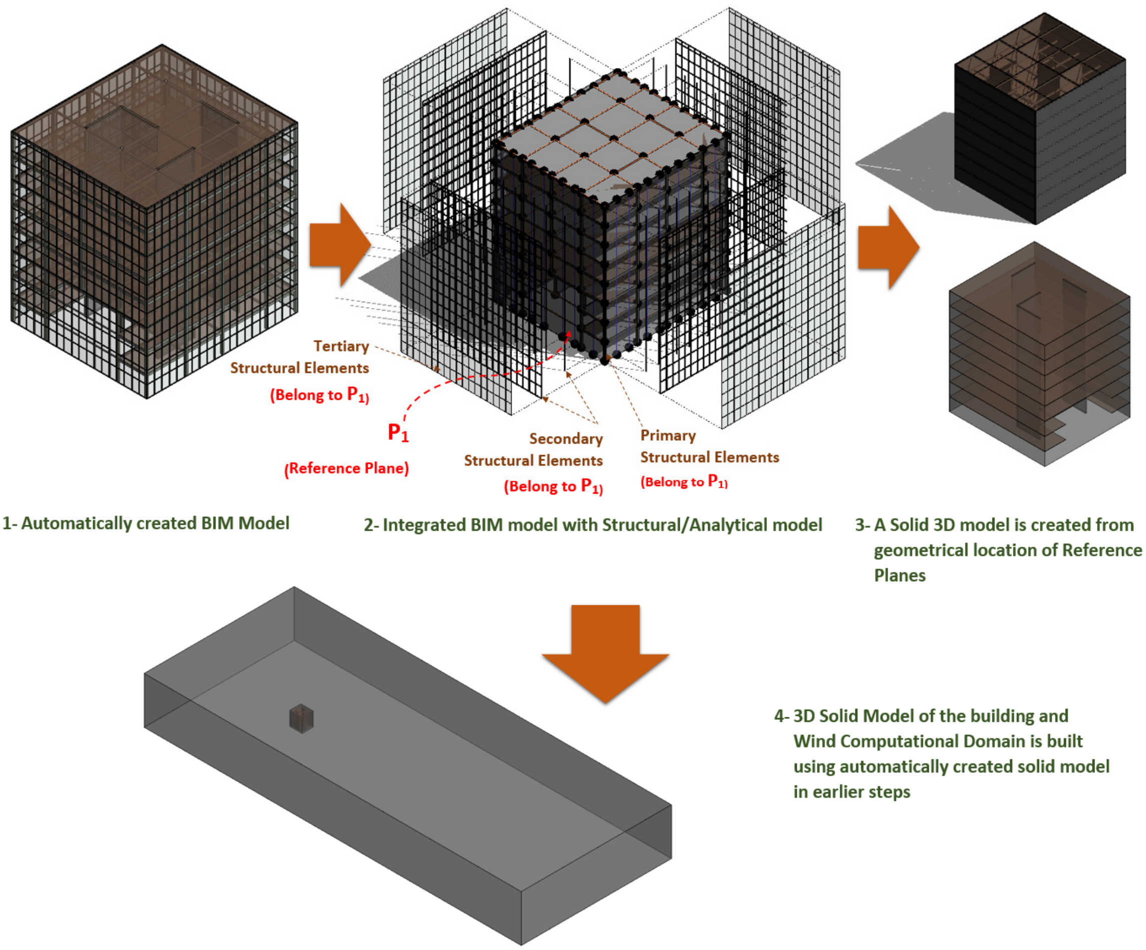

Fig. 6-12 Illustration of the Planar Concept being used to provide a geometrical reference concept for automated creation of the 3D wind model from the main BIM model while keeping it linked with the structural/analytical model (conceptual BIM model)

6.3.4 Higher LOD model for Wind simulations

Two main issues may arise when using the proposed Planar Concept approach. First, the created 3D model for CFD simulation might have some discrepancies with the actual design model regarding the size and volume due to simplifications made while creating the 3D models. Second, as illustrated in Fig. 6-12, the created 3D model of the building has a very regular and smooth surface, and the actual building façade profile is not projected on it. As surface details are one of the most important parameters affecting wind performance, the missing 3D façade features of the building are required for a more accurate definition of the wind boundary condition for the CFD simulation[23]. This lack can be addressed through a simple modification of the application of the Planar Concept.

The approach taken was to build two different data sets for probe location, a BIM set and a CFD set. Similar to the approach for the solar panel CWE case, a 3D STL model could be created of all the exterior building 3D components, addressing the problem a). To complete solving problem b) and c), all the probes in CFD model are located on the exterior face of the 3D STL model while a 2D matrix conversion is used to reference them back to the BIM model. In the BIM model, all the representative analytical/structural models are mirrored and located on the referenced plane. Therefore the probes also should be located in the same place for further triangulation and tributary area creation. This 2D conversion keeps all the Z (elevation) data of the probes considered for CFD model and mirror X and Y coordinates to be located back on the related reference planes preserving consistency between the models. BIM and CFD probes are linked but stored in two different datasets as illustrated in Fig. 6-13.

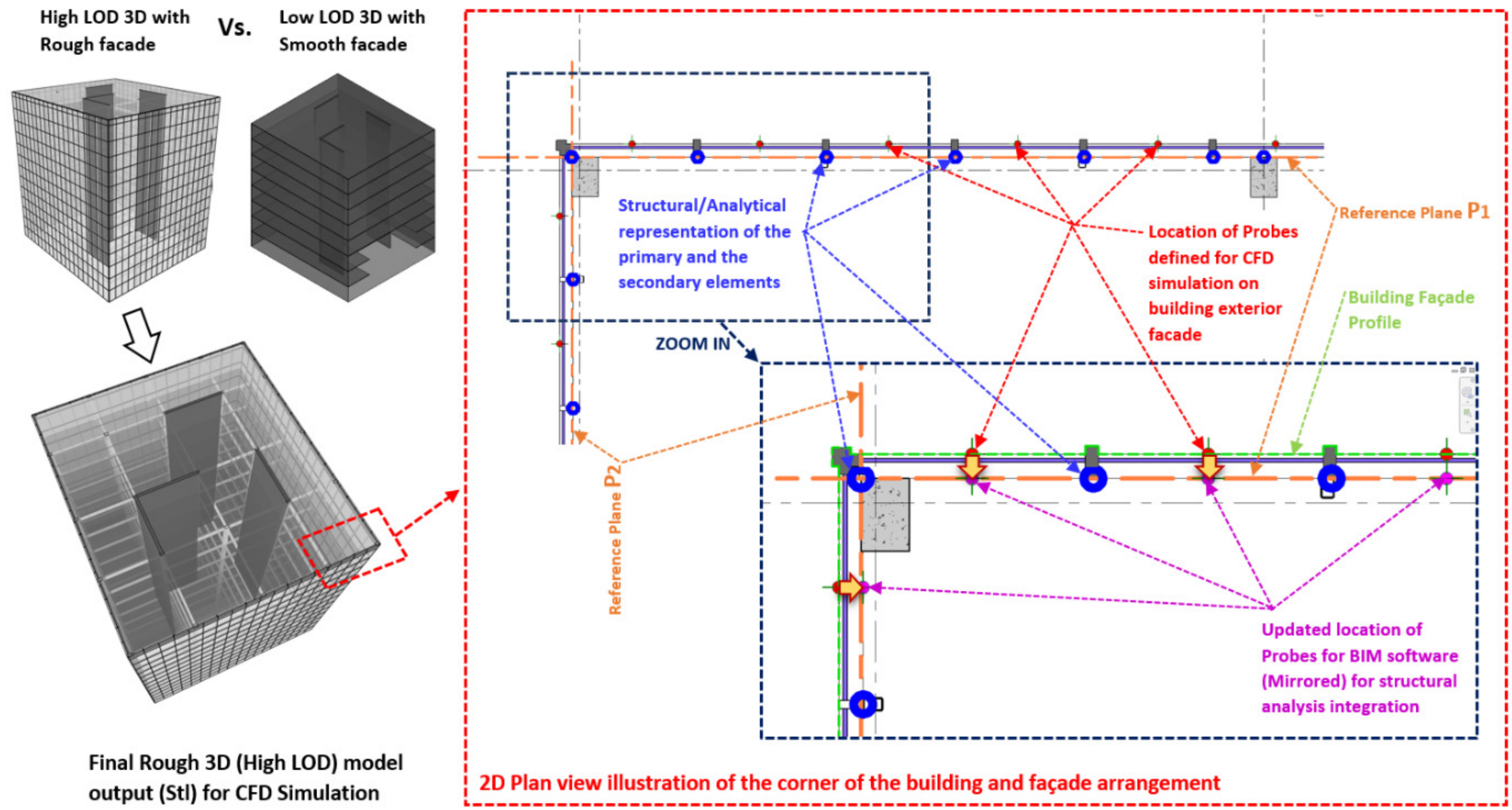

Fig. 6-13 Illustration of the modification and 2D conversion required to resolve the integration problem

6.4 Wind Engineering integration with BIM evaluation through PEB Example Project

A BIM-based software application was developed to evaluate the automated BIM model development processes and the proposed Planar Concept and Floating LOD ([9]-Chapter 5 of this thesis). Emphasis was given to the application of the Planar Concept for creating a fully automated BIM system integrating CWE. The developed application was used to model an example PEB project for evaluation purposes. The example project was a real industrial PEB building that had been designed and developed using traditional PEB design systems and processes. The initial design of this 21m x 16m x (11.53m Eave Height) Gas Compression Station was done in the absence of any BIM model for PEB structures, the building enclosure, and a collaborative environment (see Fig. 3-11).

The BIM-based software interface, built using a BIM design software API, developed as part of the current study for the evaluation processes in conjunction with some examples of the software output in the design development of the example project. The entire process of model development for the example project was done using the proposed automated process as described earlier in references [9]-Chapter 5 of this thesis

In order to develop the CFD simulation, flow characteristics, boundary conditions, and geometry/meshing criteria standard procedures suggested by [31] was followed. Some of the CFD simulation assumption and characteristic used for example PEB project are presented in Table 6-2.

Table 6-2 The example PEB project CFD simulation characteristic

The turbulent simulation assumptions and characteristic

- Reference mass density of the air, $\rho = 1.29\ Kg/m^3$
- Reference static pressure of the air, P = 101.3 kPa.
- Laminar (molecular) kinematic viscosity of air, $\nu = 1.5 * 10^{-5}\ m^2/s$
- Initial velocity in the computational domain = 0 m/s
- Inflow velocity (a) uniform velocity profile, U = 10m/s, and (b) atmospheric boundary layer
- (ABL) flow with mean velocity in m/s, U(z) = 1.9ln(20z+1),
- Turbulence intensity, I(z) = 1/ln(20z+1)
- Turbulence length scale in m, $L(z) = 12.5z^{0.6}$ where z is height above the ground surface in m.
- Building surface as smooth wall and the ground surface (with roughness length, Z_0= 0.05m) as a rough wall with roughness parameters: Von Karman constant, k = 0.4 and roughness height, r = 1.75m.

The first step is to evaluate the developed approach for creating the building and computational domain 3D model from the BIM (i.e. Solving problem (a) described in Table 6-1.The successful implementation of the developed process and API interface through integration process for this step is shown in Fig. 6-14. The STL mesh created using surfacing approach introduced on BIM building model and pre-defined Computational Domain (CD) inside BIM authoring tool. This CD information was input by the user through API software interface and was stored in the different table in the central database. It was noted that automatically created 3D model of the example PEB building in BIM design authoring software was successfully identified and discretized by the CFD simulator software.

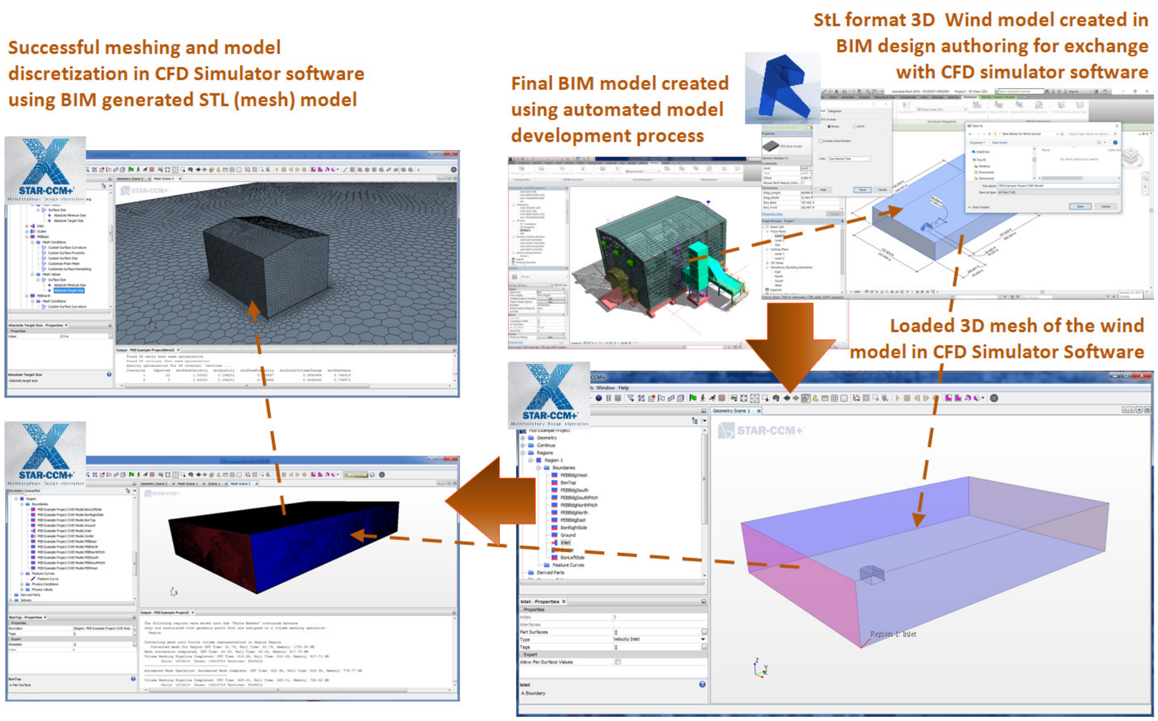

Fig. 6-14 Automated 3D model development for CFD simulation from BIM model

Solving problem b) and c) automated probe locating and data exchange (descried in Table 1) are solved as follows. As it is shown in Fig. 6-15, the global coordination of the computationally found probes (tangentially oriented to the surface) in BIM design authoring are saved in the central database. Important factors playing a role as parameters in this algorithm are the location of secondary structural elements, facial features of the buildings and the computed/visualized tributary areas. These factors are illustrated in the

API interface on the West Plane (gable side of the building) by representative lines of the secondary structural elements (analytical model), facial features (doors, openings, etc.) and the tributary areas in Fig. 6-15 (snapshots on the right side). Also translated coordinates of the referenced probes are calculated and stored in a separate table in the central database as per described process. These transformed coordinates are introduced automatically to the CFD simulator using JavaScript code (StarCCM+ API or Macro functions). As shown in Fig. 6-15 (snapshots on the left side), the 1206 number of monitoring points (probes/references) tangentially oriented to the surface of the building CFD 3D model are placed successfully in through an automated process.

Fig. 6-15 Shared Central Database for probe coordination

Using the process described in Fig. 6-6, after analysis, the result of CFD simulation are reported (for the defined probes) in ".CSV" spreadsheet which is transformed into the central database as "Values" per coordinates. Fig. 6-16 illustrates the described data exchange processes from CFD simulator to back to BIM design authoring tool for visualization and further structural analysis and design processes. The evaluation of the accuracy of the exchanged data into BIM tool is shown in Fig. 6-16 by visualization comparison in an identical color counter presentation range (color bar ranges were unified). Pressure point results (2D planar contour maps) were projected on the main building successfully using Autodesk Revit's Analysis Visualization Function (AVF).

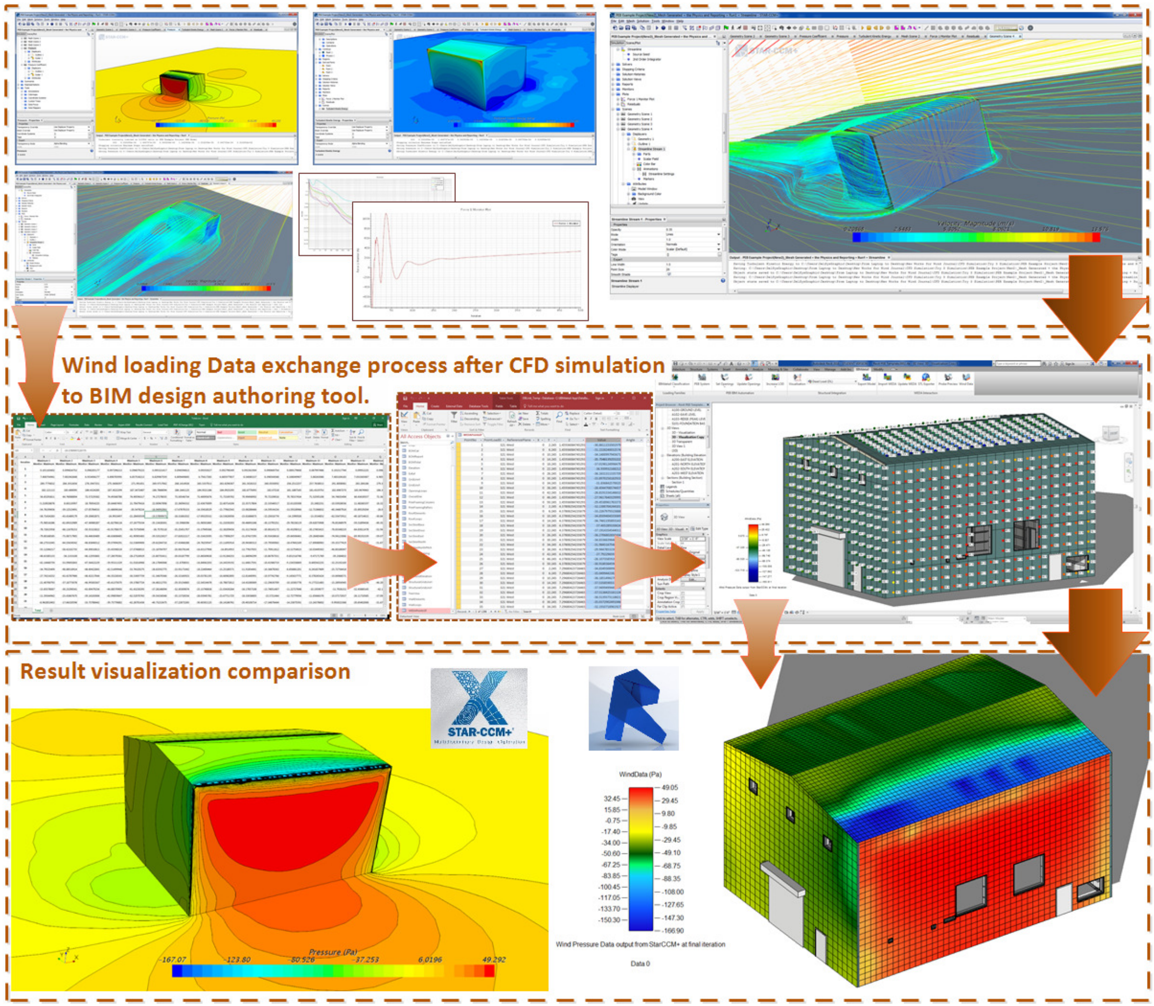

Fig. 6-16 Process of wind simulation data exchange between CFD simulation software and BIM design authoring tool using referenced probes

By showing the results and transferring the wind loading data into the design interface, the developed API was able to apply the wind load on the same plane as the structural and analytical models delivering the desired integration between BIM-based design and CWE analysis for the example project. The mentioned process, example project structural/analytical model and automatically calculated and applied loading on the building structure are shown in Fig. 6-17.

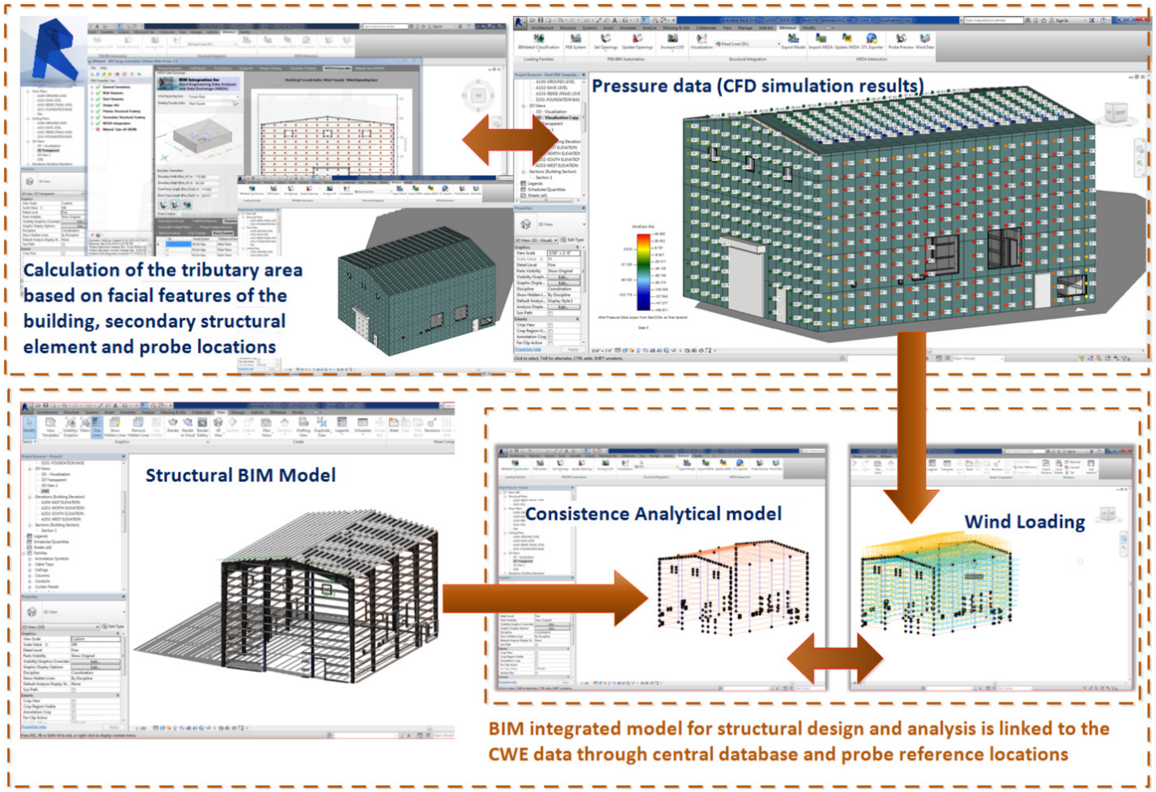

Fig. 6-17 Automated wind load calculation using referenced probes and Planar Concept

6.5 Generalization of the approach for non-PEB industry and future applications

The example PEB project illustrated and allowed the evaluation of the proposed method and resolutions for problems a) to c) for the PEB industry. However, it is proposed that a similar approach could be applied to the general construction industry. As illustrated in Fig. 6-12 and Fig. 6-13 the proposed method for creating 3D models of building and computational domain automatically from BIM model can be followed for any type of building. This is because its advanced surfacing algorithm only deals with the exterior features of the building, disregarding the building types and purposes, as a general resolution to the problem a).

Likewise, to resolve problems b) and c) for the PEB domain, the core of the approach taken was the use of a central database and intelligent locating of probes (reference points) thus supporting data exchange between the modeling and analysis tools. For the general construction sector, a link of information between modeling and analysis tools could be achieved through a similar application of a central database and by arranging the global probe location matrices for lower LOD case and transitioned matrices for higher LOD models for simulations. Finding the global coordinates (location) of the probe while keeping them tangentially oriented to the surface can also follow the same process and algorithms based on the exterior features of a building.

The only difference between PEB and conventional building that needs to be taken into account is that the 2D planar locating of probes and tributary areas will vary depending on the material classification and construction. The proposed algorithm can be modified for general industry (conventional building) by developing material/construction specific classification data for facial featuring, probes location and calculating tributary areas. Thus, the proposed method for BIM and wind engineering integration can also be extended to be applicable to general construction industry. A case study conventional building could be examined for such a claim in further research.

The fully automated model creation and data exchange between CFD and BIM model provide two new capabilities to wind engineering researchers. The first is dynamic boundary allocation and the second is integrated multi-scale and multi-physics simulation. As an example, for the first, the vertical and horizontal building openings (such as open windows, air intakes, and elevator shaft openings) can be modeled as air domain (i.e. non-solid) in the 3D model. Therefore, the automation can be creating different 3D CFD models for different airflow scenarios for the building when studying the features of the air movement inside the building. In the second case, multiple façade profiles can be easily configured for CFD study based on BIM model variants. This supports examining different façade failure scenarios and climate performance (wind, thermal, moisture, etc.) of the building accordingly. Failure studies include the possibility of setting elements of the 3D façade model to be treated as part of the air domain in the exported STL model for CFD simulation to mimic component failure.

Conclusion

A comprehensive discussion on the application of BIM for engineering design processes is presented in this paper. In particular, the discussion on the BIM and engineering design integration was narrowed to Wind Engineering and BIM collaboration. A detailed process map was developed defining data exchange strategies and the application of a "central database" to deliver integration between BIM design and Wind Engineering, for both wind tunnel and CFD based approaches. To enable effective integration between the BIM and CFD models two key modeling attributes need to be defined and maintained. Firstly, a unified referencing coordinate base system needs to be created in the database for use when setting probe positions and reporting probe values. The coordinate system developed for this purpose was also designed to accommodate the natural differences between BIM and output CFD models through the use of the Planar Concept. Secondly, a strategy and approach for creating and transferring 3D models between the BIM design authoring tool and CFD simulator software. The performance of the developed concepts and processes were evaluated through developed BIM-based design software as applied to an example PEB building project. The results show the developed mechanisms supported the desired data exchange processes and were successful in providing an integrated BIM-design and CFD analysis environment. The flexibility and ease of the system could significantly reduce the cost of the design by reducing geometric modeling times during wind evaluation activities, and by extending the number of engineering disciplines that can collaborate on designs using BIM design technology.

Acknowledgement

The authors would like to express their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial support this research was developed.

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Chapter 7

7 Relative Concept for automation in BIM material quantification and 5'D BIM Coordinated Procurement System

Abstract

Material take-offs (MTOs) are costing are very significant activities in all construction project processes. Current dominantly CAD and specification based MTO and costing activities are often done manually. Building Information Modelling, with its rich component models, allows for much more rapid and automatic extraction of quantities and related costs. However, BIM is not a perfect solution and current implementations have challenges and limitations related to the completeness of the model and the time/effort to develop the models. These issues limit the accuracy of costs and quantities generated and relegate their use to be solely as estimates.

Earlier work by the authors investigated using BIM to improve design flexibility and collaboration in the Pre-Engineered Building (PEB) industry by replacing its proprietary CAD systems with a BIM based approach. The proposed approach maintained the highly automated and integrated design workflow that allowed the PEB industry to go directly from design all the way through to costing and procurement activities. The impact of automated design resulting in high Level of Development (LOD) 5D BIM models on the MTO and cost estimation activities is reviewed in this paper. Furthermore, the 5D BIM model concept is extended (called 5'D in this paper) into subsequent purchasing and procurement activities where the accuracy of the MTO and costs is extremely important.

Keywords:

Building Information Modeling (BIM), Material Quantification, MTO, BOM, 5D BIM, 5'D BIM modeling, BIM Coordinated Procurement System, BIM LOD, Purchase Requisition, Pre-Engineered Building (PEB)

7.1 Introduction and Background

7.1.1 Material quantification (take-off) MTO/QTO and Bill of Material (BOM)

As defined by the International Society of Automation (ISA) [1], material take-off (MTO or in other references Quantity Take-off, QTO) is the process of analyzing the drawings and determining all the materials required to accomplish the design. The results of the material take-off are then used to create a bill of materials (BOM) and subsequent procurement and requisition activities directly rely on the completed BOM[2]. A BOM or product structure is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture an end product. A BOM may be used for communication between manufacturing partners or confined to a single manufacturing plant. A BOM is often tied to a production order whose issuance may generate reservations for components that are in stock and requisitions for components that are not in stock[3].

7.1.2 Standard Purchasing system (Procurement system)

Purchasing is the formal process of buying goods and services. The purchasing process can vary from one organization to another, but there are some common key elements. The process usually starts with an expressed demand or requirements – this could be for a physical part (inventory) or a service[4]. A Purchase Requisition (PR) is generated by the procurement department, which details the requirements (in some cases providing specifications). The procurement department then raises a request for proposal (RFP) or request for quotation (RFQ). Suppliers respond with their proposals or quotes, and a review is undertaken where the best offer (typically based on price, availability, and quality) is given the Purchase Order (PO). Purchase orders are normally accompanied by terms and conditions that form the contractual agreement of the transaction. The supplier then delivers the products or service, and the customer records the delivery (in some cases this goes through a goods inspection process). At some point, an invoice is sent by the supplier that should then be crosschecked (by the customer) with the original PO and records of goods that have been received. Payments are made and transferred to the supplier if everything checks out [5].

The core process of purchasing in any construction industry organization is to most extents similar and there are even standards, e.g. ISO 9001, published by standards organisations like International Organization for Standardization (ISO) and European Committee for Standardisation (CEN). Particularly, as purchasing and procurement systems deal with multidisciplinary and enterprise level activities[5] several major software vendors have integrated support for procurement processes and workflows into their Enterprise Resource and Planning (ERP) packages.

7.1.2.1 ISO 9001purchasing procedure

Purchasing procedures under ISO 9001 are designed to ensure that purchased materials meet the requirements of the purchaser and the final customers. Companies apply ISO 9001 to their processes to reduce waste and minimize problems with their products and services. When practiced consistently, purchasing according to ISO 9001 standards should result in continuous improvement in company operations. Purchasing procedures require documentation that ensures the purchased material corresponds to the technical specification and budgeted cost. Procedures typically specify that the purchase order refers to the relevant parts of the technical specification and require that the purchaser check the current estimates before placing an order, making sure the amounts are within budget. Purchasing procedures that comply with ISO 9001 also specify that the company can only purchase from suppliers qualified for the items on the purchase order[6–8].

7.1.2.2 SAP Enterprise Resource and Planning (ERP) procedure

SAP Enterprise Resource and Planning (ERP) software is developed by the German company SAP SE. It is intended to incorporate the key business functions of an organization[9]. SAP has incorporated the ISO standards for all its procedures (ISO 9001 and ISO 27001) and created reports through standard procedures and forms[10]. SAP ERP's standards compliant functionality and multi-year record of deployment by large corporations has made its system and software solution to be an internationally accepted platform for deploying companies.

SAP ERP contributions and influence on the construction industry was assessed to be sufficient to warrant using its implementation of ISO procedures as representative of common industry practices when developing a BIM coordinated procurement system for two key reasons. First, in North America paper-based business management systems (where all the forms are filled out manually and handwritten) have generally been replaced with electronic document management systems. As an example, the current estimates from ARMA (Association of Records Managers and Administrators) indicate that more than 90 percent of the business records created in Canada are electronic[11]. Therefore, any BIM-based system and associated processes should be defined so that it can work with electronic document management or ERP software, with SAP ERP being a suitable example case study. Secondly, SAP ERP has an elaborate tool set and set of procedures for purchasing for use in the engineering manufacturing industry. This matches well with the authors' research focus on developing an implementation of BIM for design and construction in the Pre-Engineered Buildings (PEB) industry and the related development of automated processes to integrate with different disciplines including purchasing and procurement. Purchasing and procurement is a key element of business for construction industries, such as PEB, that deal with manufactured engineering products and SAP ERP systems have been observed in general deployment in them. Fig. 7-1 illustrates the SAP ERP workflows and how they are represented in its interface.

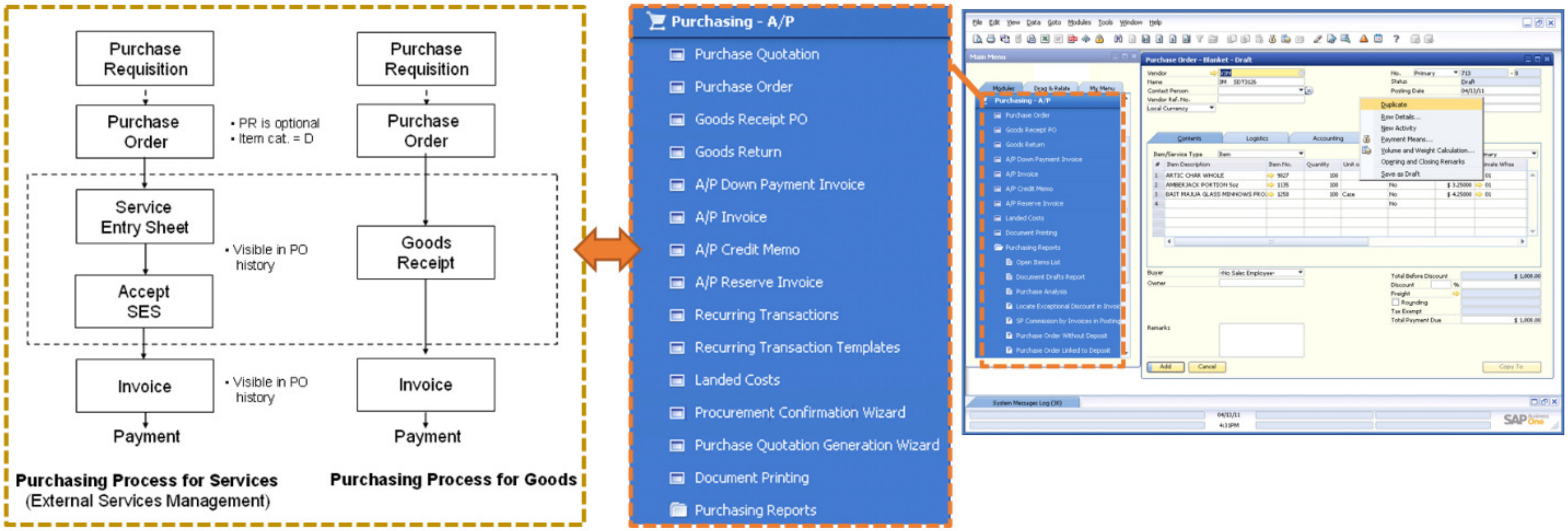

Fig. 7-1 - SAP ERP purchasing workflow and software interface (purchasing panels) [12]

For the purposes of this paper, the important aspects of the procurement process flow are illustrated in Fig. 7-2. For these ISO processes to work, reliable requirements information needs to be provided to the procurement system in a “Purchase Requisition” format. In the PEB industry, when using a BIM system, the input point into procurement system is also the integration point with Engineering Design and Drafting Department. This integration between sales of PEB products and procurement of the materials that make them and a way to address the difficulties that occur at this interaction stage (purchase requisition) are discussed in this paper.

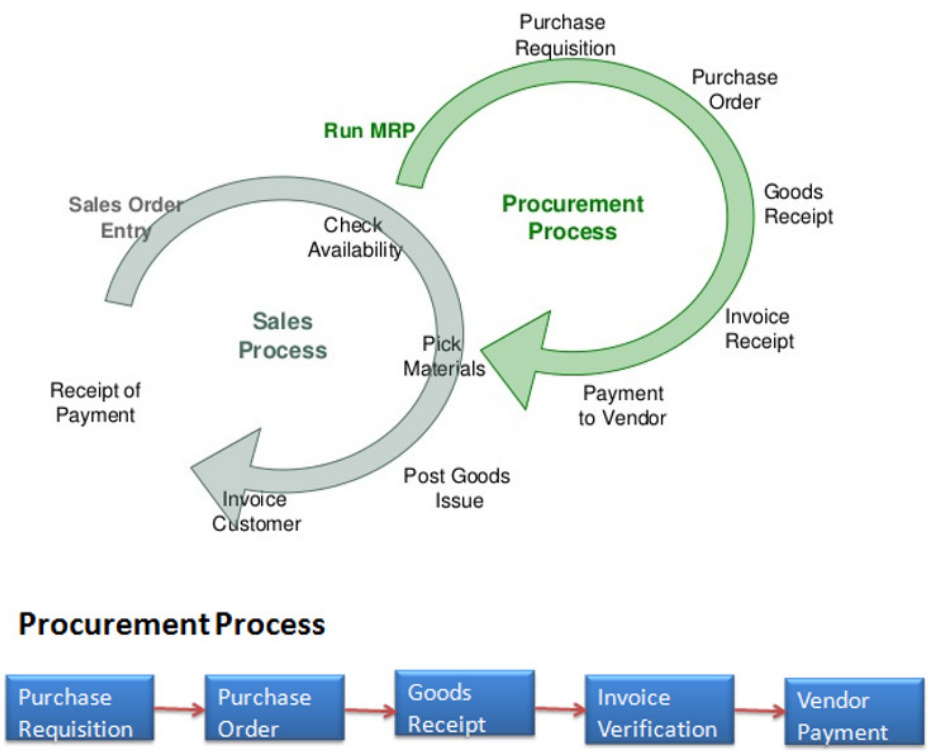

Fig. 7-2 - Procurement Process from Material Requirement Planning (MRP) to Sales order flowchart suggested by SAP ERP system[13,14]

7.1.3 5D Building information modeling (BIM) Vs. 5’D contribution for MTO and procurement system

Cost estimation of construction projects is a very complex process containing many variable factors. This skill is not easily acquired. Study, training, and experience are needed to become proficient in construction project cost estimating. There are several categories of constituent costs that can significantly impact overall project costs. The estimator needs be familiar with them and properly evaluate their effects, before finalizing any cost estimate. The first and principle step in cost estimation is the extraction of information from the design and the development of the corresponding BOM[15]. To achieve the required accuracy this is typically a very time-consuming process when performed manually and often introduces numerous human errors.

4D BIM modeling links the construction activities represented in time schedules with 3D BIM models to develop a simulation of construction progress against time, often reviewed visually. Adding the 4th dimension of time offers an opportunity to evaluate the buildability and planned workflow of a project. Project participants can effectively visualize, analyze, and communicate problems regarding sequential, spatial and temporal aspects of construction progress. Consequently, much more robust schedules, and site layout and logistic plans can be generated to improve productivity. Integrating the 5th dimension ‘cost’ to the BIM model generates what is anecdotally known as the 5D model. This 5D model is meant to enable the instant generation of cost budgets and generic financial representations of the model against time. This use of BIM reduces the time taken for quantity take-off and estimation from weeks to minutes, improves the accuracy of cost estimates, minimizes the incidents for disputes from ambiguities in CAD data, and allows cost consultants to spend more time on value improvement[16]. 5D models require established project work breakdowns (WBS) referenced to 3D model elements. Therefore, 5D modeling should be established on top of 4D models for maximum accuracy of final costing. However, by far, most research and publications treat 5D BIM models as merely additional cost information added to base 3D models (i.e., references [17–21]) limiting the model application to mostly supporting cost estimates during the estimation and bidding phase of a project (also know as early stage cost estimation[22]).

However, BIM guidelines such as “Penn State BIM execution planning” suggest the application of BIM cost estimating can be extended to later construction phases[23]. With sufficient development, BIM models can be directly used as input when developing Purchase Requisitions. In this scenario, knowing the status of material/building components in the purchasing process could help designers and engineers deal more cost-effectively with changes in the design (change orders) in tightly scheduled or fast track projects. Any decisions between options for addressing change orders could then be based on far more accurate knowledge of cost implications. This would include costs of any new work, the presence of any already acquired materials as well as procurement timelines for newly needed material or services. In many cases, avoiding changes to parts in the design that have been ordered or processed by the purchasing department could reduce undesired overhead or materials waste costs. However, obtaining this information, which is frequently updating, requires multidisciplinary communication, defined responsibilities, and accountabilities and thus consequentially leads to added complexity.

In this paper, the term 5D BIM is used to cover models that include sufficient information to support cost estimation during estimation and bidding phases of a project. In contrast, the term 5'D BIM is used to cover models with information sufficient to support costing during fabrication, procurement and construction. Fig. 7-3 illustrates the similarities and overlap between the 5D and 5'D BIM as well as differences regarding the process flow and involved disciplines.

As presented in Fig. 7-3, it is essential to clarify the differences between 5D BIM and 5'D BIM regarding the difference in the area of operation, involved disciplines and discrepancies in the procedure, when developing a comprehensive process and framework for the integration of project cost related issues and BIM.

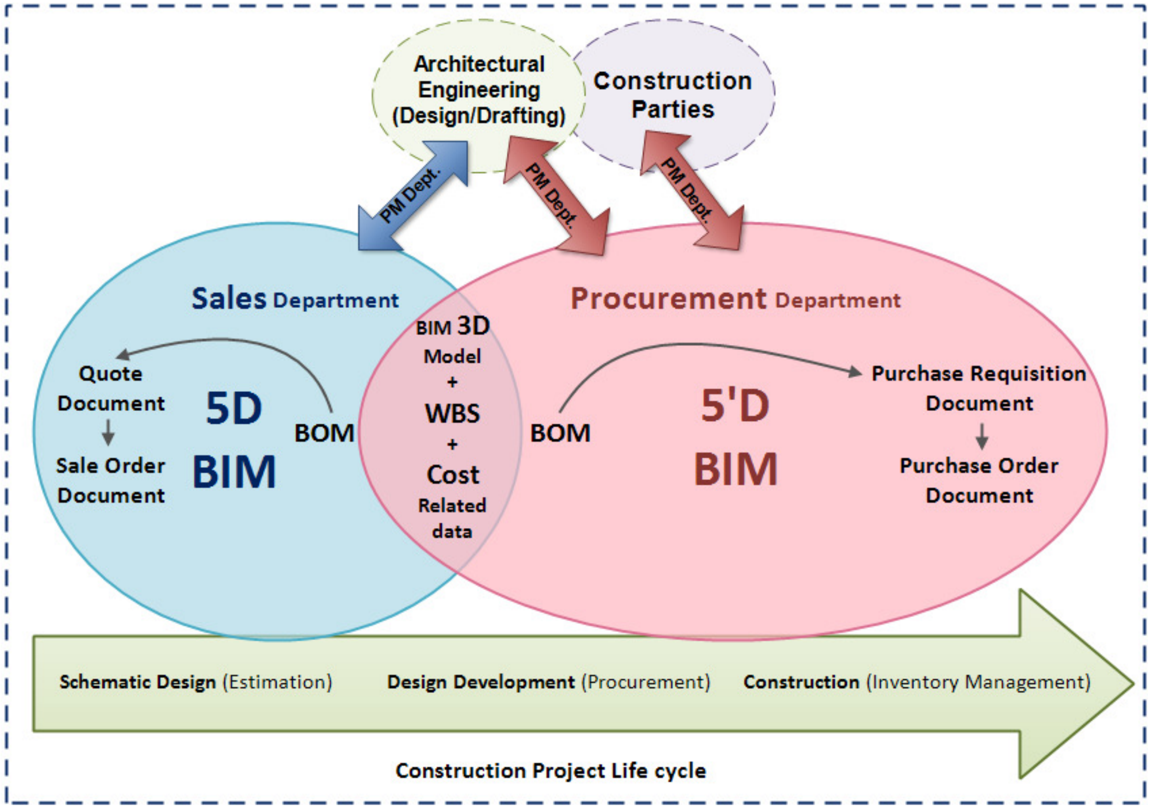

Fig. 7-3 - 5D BIM process Vs. 5'D BIM process

Another important difference between 5D (during initial estimation) and 5’D (for use in procurement and construction) is how 5’D involves the expansion of the details of each WBS during design development. WBS are often established in the initial phases of each project and it is important to maintain documentation of them over the project duration[24]. When using BIM models, each WBS can be linked to model entities that may later be replaced by more detailed elements or decomposed into collections of entities as the Level of Development (LOD) of the BIM model increases after the initial estimation process. In these cases, the WBS should be updated accordingly to match the development of the project design. As a result, the 5D WBS would need to be replaced with more current 5’D WBS. The challenge in doing this arises partially due to the difficulty of tracing the evolution of the 4D model (3D model + schedule/WBS) and then linking that into the 5’D model where cost is determined and monitored.

7.1.4 Aim of the research

This paper presents the results of evaluating the benefits of developing a practical BIM framework for the PEB industry which deals with cost related issues([25]-chapter 2 of this thesis). The main idea of incorporating the use of BIM for the management of cost related issues through to the end of a project (5D BIM vs. 5'D BIM) comes from the traditional PEB integrated (and automated) design to delivery workflow. It is expected that most fabrication and manufacturing construction industries could benefit from using standards based processes and procedure due to the repetitive nature of their work and close links from design to their production lines. The PEB industry has a unique proprietary design development, manufacturing, and installation process which is called "single source responsibility" ([25]-chapter 2 of this thesis). This process covers a PEB building lifecycle from the design phase to hand over for operation. Because of this, it covers both sales (5D BIM area of integration) and purchasing activities (5'D BIM).

The PEB industry currently uses a CAD-based (non-BIM) system that efficiently manages the cost related issues by automating and integrating the process of MTO and sales and purchasing. This One efficient and digital management of cost is a key strength of traditional PEB industries. However, their proprietary software systems approach has a significant drawback in that it inhibits collaboration with external stakeholders, including designers from other disciplines, due to a lack of any broadly effective data exchange mechanisms. In ([25]-chapter 3 of this thesis) a BIM framework based approach was presented and shown to be able to improve design collaboration and project coordination in the PEB industry.

The goal of this work is to leverage the BIM framework and models to support the acquisition and management of cost data as effectively, or better than, as managed in traditional PEB systems. To develop such an effective system to manage cost data a) the process of MTO should be automated as much as possible to require minimum labour and to eliminate human errors, and b) an effective 5D, 5'D BIM coordinate system should be developed to deal with cost management issues that arise after the initial estimating phase.

To evaluate the cost management concepts and approaches developed, a BIM-based software application was developed and the procedures and the performance of the system were evaluated for an example PEB project.

7.2 Challenges and Barriers to BIM-assisted MTO and procurement system

The results of national and international BIM surveys such as NBS and SmartMarket [26–28]indicate a positive trend in BIM adaption and implementation in general construction industry, but they also illustrate the current immaturity and difficulty using BIM for cost management (5D BIM). As an example, the results of the 2012 SmartMarket Report survey of industry [27] (presented in Fig. 7-4) indicates poor value was being received for efforts to use BIM for 4D and 5D BIM modeling for schedule and cost management during preconstruction activities. In contrast, the use of BIM for 3D spatial coordination was found to be of good value/difficulty. Worth noting is that BIM software vendors such as Autodesk and Vicosoftware over last decade have been steadily improving their offerings support for BIM MTO in BIM design authoring and review software[20,29].

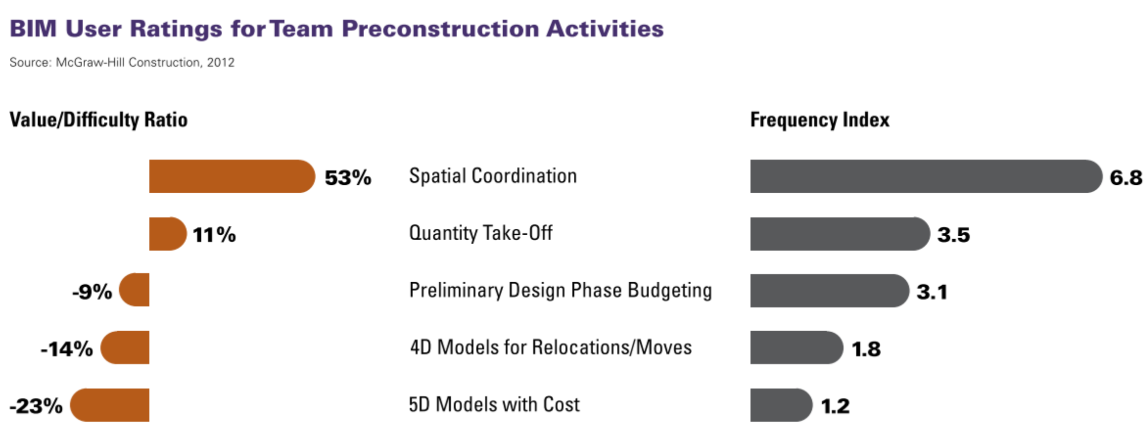

Fig. 7-4 – Results of the survey on Value/Difficulty Ratio and Frequency Index for BIM-based MTO and 5D (in estimation and design - preconstruction phase) [27]

The same survey results on the application of BIM for cost management issues during design/construction and procurement processes (called 5'D by this paper) had even lower value/difficulty outcomes (illustrated in Fig. 7-5). This indicates the extension of BIM to 5'D applications remains a work in progress.

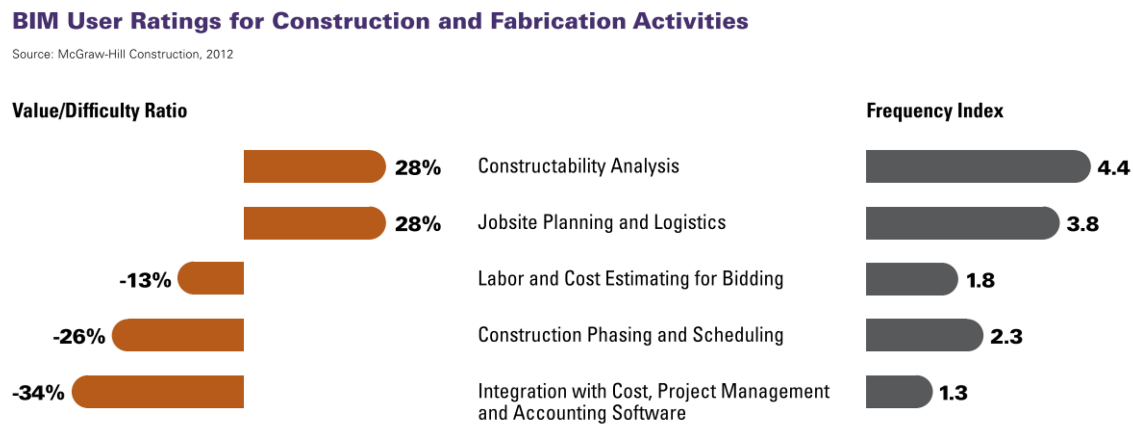

Fig. 7-5 - Results of the survey on Value/Difficulty Ratio and Frequency Index for BIM-based MTO and 5'D (in design and construction/fabrication phase) [27]

The main challenges for 5D and 5'D BIM applications can be grouped into two separate categories of related issues.

7.2.1 LOD challenges for 5D BIM model based MTO

Research on 5D BIM applications by Peter Smith[19] indicates that the quality of the BIM models is the major concern for most BIM-based MTO. To develop BIM models sufficiently for accurate MTO requires the input of significant amounts of interconnected data and information that is typically complex in nature. While BIM models support clash detection, most tools will only perform basic geometric comparisons and in some cases proximity checks and will thus not validate all information. Clients also need to be prepared to budget sufficient resources to complete the proper development of a quality model that contains sufficient geometrical and non-geometrical information required for MTO. The concept of 'Rubbish In Rubbish Out' certainly holds true for cost estimation. The risk and liability from the use of inadequate or incorrect information in the model is also a major concern[19].

Research based on different national BIM guidelines and studies reviewed the importance of LOD for BIM applications and identified a current sweet spot or hypothetically optimum LOD of around 350 ([25]-chapter 4 of this thesis).

The illustration in Fig. 4-4 in chapter 4 of this thesis, M. Delavar et Al. shows the hypothetical optimum LOD level that BIM models need to achieve to support most common BIM applications, including automated MTO (QTO). The illustration in Fig. 4-4 in chapter 4 of this thesis, also shows that the process of developing the BIM models to the optimum level can be time-consuming and costly using existing non-automated BIM design systems. Automation was thus seen as a likely effective way to repeatable and reliably achieve the necessary model development that is critical to the successful completion of MTO activities. The question is how to sufficiently automate the BIM-based modelling MTO processes (covering all the project materials) so that all procurement and cost information can be directly driven from the resultant BIM 3D model.

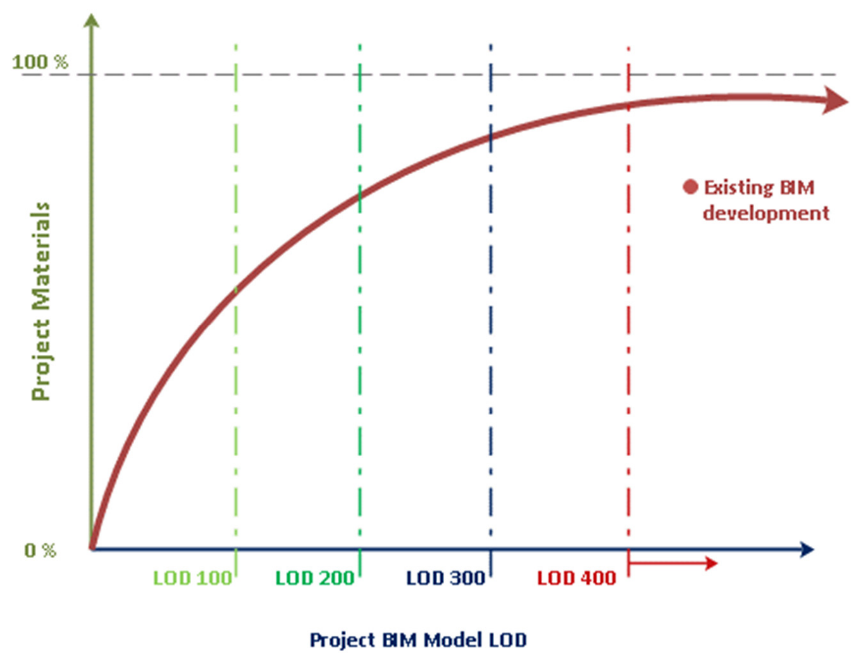

Fig. 7-6 - Project Material quantifications completion Vs. BIM Model LOD Development

In general, as illustrated in Fig. 7-6, the more complete or finalised a model is (specifying actual components and not generic place holders) the more accurate any MTO will be. However, there is a point of diminishing return around LOD 400 where almost all significant systems have already been specified to the make and model level. Other small materials are generally not worth modelling, or may be impossible to accurately model as their use is dependent on the construction site crew and their efficiency in materials usage (e.g., screws), as well as materials which can not be efficiently modeled in a BIM environment such as liquid mortars used in between brick system or used for stone installation. In general, these items will have a minor or negligible impact on total material quantifications, with the exception of special cases beyond the scope of this paper (e.g. projects in an isolated area without access to a warehouse or material shop). Thus, after LOD 400 any further development of the BIM model becomes ever more time-consuming and costly while not substantially contributing any more value to the MTO process.

7.2.2 Challenges with 5'D BIM coordinated procurement system

As previously presented, procurement departments want to adhere to standard ISO based processes (illustrated in Fig. 7-1 and Fig. 7-2) including the quality of the input MTO information. The objective is to have a smooth flow of information from the MTO to the BOM format to the PR to the PO, using ISO compliant systems like SAP ERP.

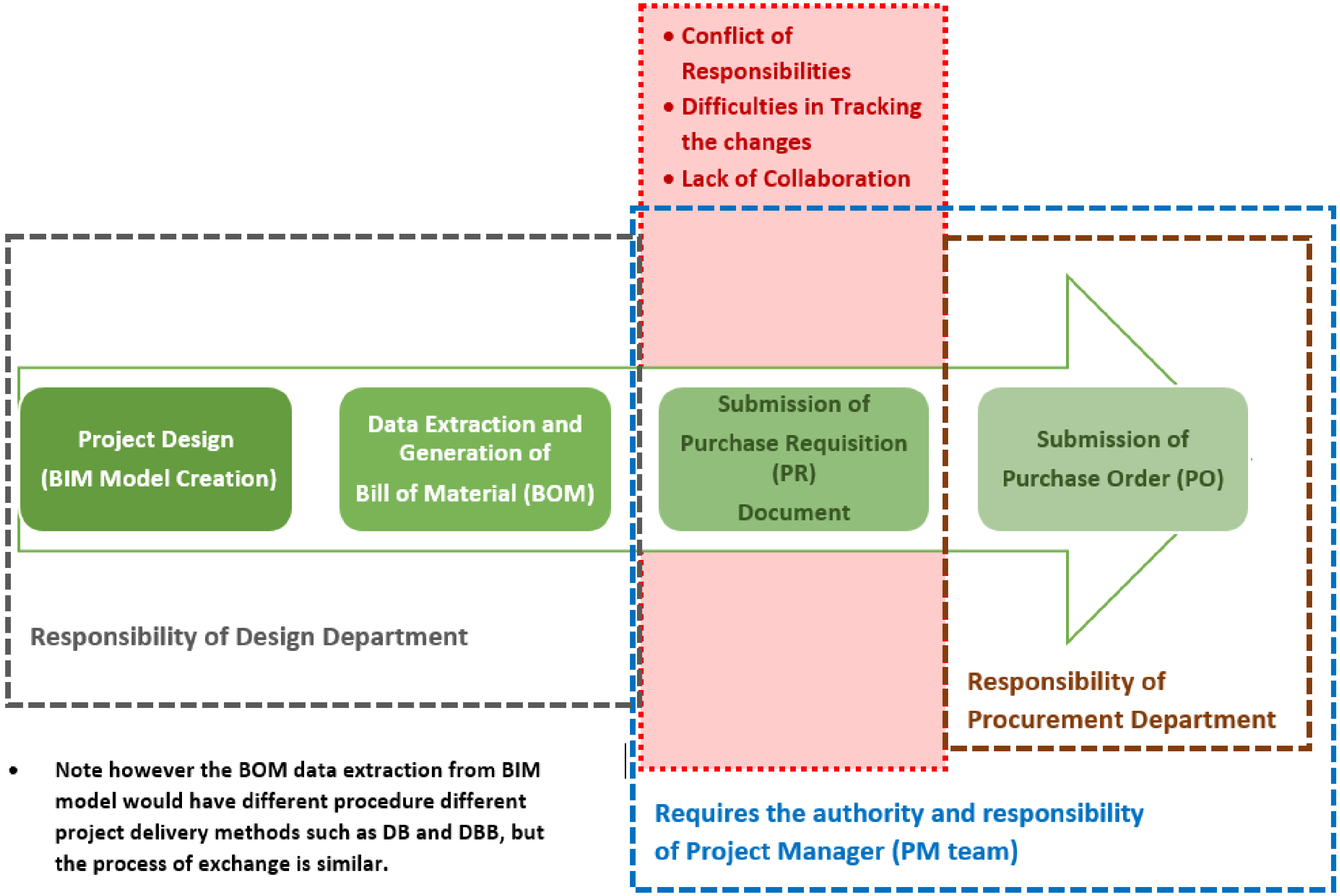

Fig. 7-7 - Addressing the BIM Design Drafting, Project Management and Procurement department interaction challenges in "Purchase Requisition" submission stage (using ISO processes)

As illustrated in Fig. 7-7 this is a multidisciplinary data-exchange which involves different parties. Initially, the Design or Drafting (Architectural/Engineering) department will be involved in the development of the design leading to the BOM development. The Project Management department will be involved in all managerial processes, including checking and approvals. Eventually, all the procurement processes are accomplished by the Procurement department after project management approvals based on the finalised BOM. As shown in Fig. 7-7, based on the SAP's implementation of ISO processes, BOMs and PRs have different formats despite containing similar information (regarding the numbers), which can cause confusion. The key point to understand and to address is the critical data hand over for the creation of purchase requisitions. Some of these challenges are listed in Table 7-1.

Table 7-1 - Different issues in BIM Integration with Procurement

Issues	Descriptions
a	Human Error in reporting BOM to procurement department in Purchase Requisition document format (materials can get ordered multiple times by mistake, or missed in the list)
b	Changes in the design are not reported to purchasing department, regarding the issued "Purchase Requisition" document of the changed elements.
c	Status of Procurement of elements is not reported to design department, as there is no standardized means to perform such collaboration comprehensively.
d	Even if the procurement status is reported to design department, finding and tracking the changes is a difficult task for designers to follow.
e	One of the major managerial issues with the purchasing and design department is a lack of clarity in the responsibility of each stakeholder toward the generation of documents and information and material tracking.

In can be seen from the different issues presented in Table 7-1, most problems are caused due to inconsistencies between the BOM (as the output from design drafting department) and the PR (as the input required by procurement department). Based on a case study examining project issues (such as Non-Conformance Report (NCR) audits, change orders, reworks, etc.) in a PEB project, about 26% of issues are caused due to lack of collaboration between the Design and Procurement departments ([25]-chapter 2 of this thesis).

7.3 Resolving the 5D BIM challenges

As discussed earlier in section 7.2.1, achieving the effective MTO using 5D BIM models requires addressing how to get the models to the minimum required LOD levels and supporting 100% material take-off when models themselves do not typically represent 100% of the final constructed building. This section introduces two concepts/approaches that were developed to address these issues.

7.3.1 Optimum LOD and Floating LOD concept

As illustrated in Fig. 4-4 in chapter 4 of this thesis, the general objective for automating the process in this research was to reduce the time required for a BIM model to be developed to a hypothetical optimum point/level. As described in ([25]-chapter 4 of this thesis) the initial model LOD target was 300, which is sufficient to support initial cost estimation data needs.

A "Floating LOD" concept was proposed by the authors ([25]-chapter 4 of this thesis) that would allow switching between different LODs by using automated design to generate the appropriate granularity (LOD) of model information to the task at hand. Designers focus on specifying the design initially at a system level (e.g. cladding, structure, etc.) and then use automation to convert those descriptions into their constituent elements in the model when higher LODs are required. Details of how this approach is an extension of BIM attributes and parametric families is beyond typical building sub-components (i.e., doors, windows, kitchen utilities), to larger components and systems can be found in [30] and is beyond the scope of this paper.

7.3.2 Relative MTO concept

Fig. 7-6 illustrates the main problem with the BIM model centered MTO, which is the difficulty in quantifying all (100%) of the project material, despite the expansion of 3D modeling to higher LODs. A relative material quantification approach is proposed by this paper (illustrated in Fig. 7-8), to overcome the explained difficulties.

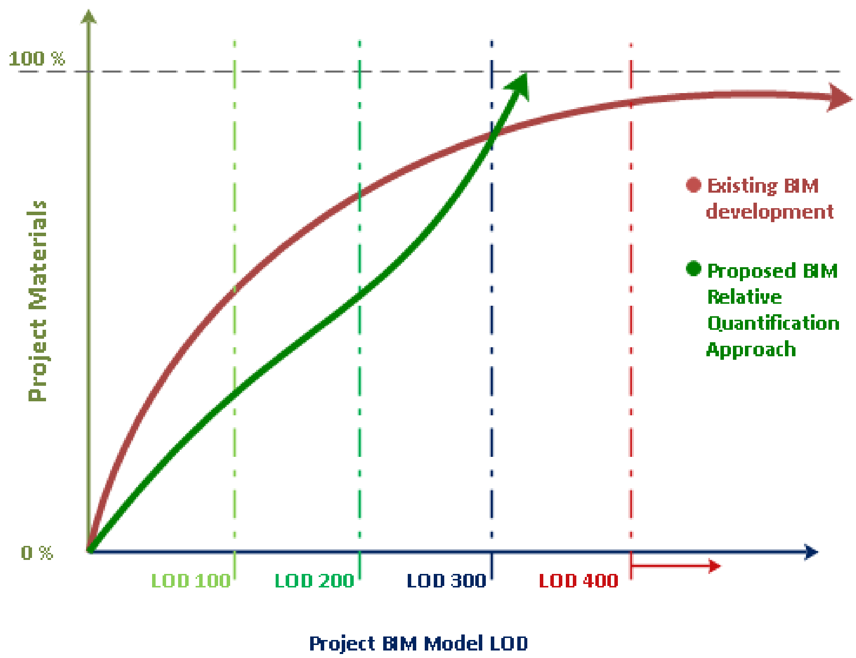

Fig. 7-8 - Proposed relative MTO approach as a resolution for complete material quantifications

This proposed relative MTO concept has been developed on the "backbone" of earlier achievements in automating the development of the model to achieve higher LOD levels. As mentioned earlier, it is suggested that LOD300 would as the target output of an automated BIM model development process covering more an approximated range of 80% to 90% of the materials in the project. Take-offs and costs for the remaining building components would be acquired using two separated approaches to obtain 100% MTO using the system (Fig. 7-8).

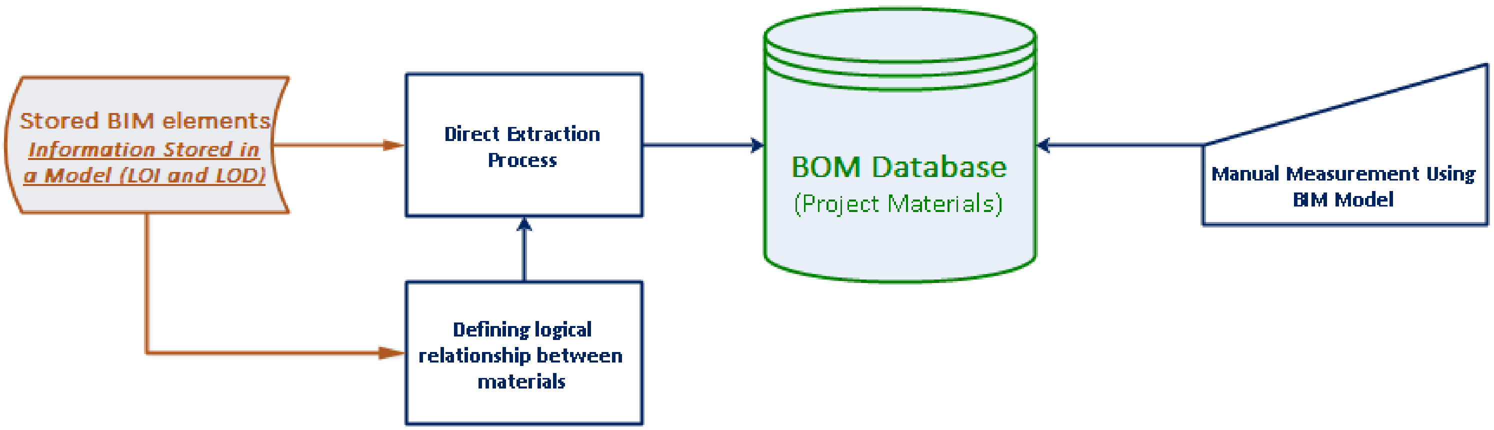

Fig. 7-9 - Relative BIM MTO process

Fig. 7-9 shows the BOM database (project material) could be filled with data accusation using three different approaches. As mentioned approximately 80% to 90% of the materials quantities can be taken automatically generated directly from the automatically developed BIM model and the amounts of other remaining materials can be obtained, in a semi-automatic fashion, based on their relationship to automatically taken off material. For example, the square footage of walls requiring painting can be directly determined from the interior surface of the modeled wall, or its sub-assemblies such as dry walls. The estimator has traditionally used this approach and it is still suggested as a common procedure in manual take-off [15] guides. To further automate this procedure this type of the "Relative" information can be embedded as relationships in the model elements and saved as a template and loaded whenever/wherever is applicable.

Even using this indirect procedure (Semi-Automated take-off), some remaining material may be left unaccounted for (elements that do have not any 3D model reference). For such materials a manual approach will be required based on measurements extracted from the model. In these cases, it is preferable to perform any required measurements and subsequent mathematical calculations, digitally in-place, facilitated and assisted to some extent by the BIM viewing environment. For instance, using BIM 3D and 2D views and snapping options, almost any measurement can be performed inside BIM viewing tools and even stored, summarized and linked to the defined related elements. As illustrated in Fig. 7-9, the remaining manually derived information can then be transferred into the BOM database.

As discussed, there have been some attempts to address this type of manual 2D take-off by some major software vendors. However, the main difference, between what is proposed here and their approaches, is that the whole operation is done in the BIM design authoring software. Relying on a single authoritative design model and keeping all the materials in one united central database is an essential factor for creating a united 5D and 5'D BIM system which is discussed in the next section.

These three approaches have their own limitations and difficulties but by using each of the three where appropriate could significantly improve the material quantification process accuracy. These advantages and limitations are summarised in Fig. 7-10.

	Can adopt the changes	Flexible toward model inaccuracy	Flexible toward lack of geometry
Direct QTO Data Extraction from BIM model	✓	✗	✗
Relative BIM Material Quantification	✓	✓	✗
BIM-Based Manual take off	✗	✓	✓

BIM relative material quantification approach covers all the existing limitations in BIM material quantification

Fig. 7-10 - Relative material quantification approach will bring flexibility to BIM MTO processes

7.4 5'D BIM coordinated procurement system

As covered when discussing Fig. 7-7 most of the issues regarding 5'D BIM integration occur at the purchase requisition development stage, where BOM information needs to be transformed into a purchase requisition format. In particular, most of the difficulties are related to the lack of defined collaboration mechanisms and proper communication between procurement and design drafting department. One approach to deal with this would be for regular meetings between the departments to share and monitor the material MTO and procurement data processes, but this is labour and resource intensive and still leaves the possibility for human error. Alternatively, a shared access database (shown in Fig. 7-9 as BIM or material database) populated with MTO data taken directly from the BIM models using available reviewing tools and reflecting procurement states could address communications challenges between design, procurement and management departments. With this approach the MTO/BOM data can be monitored by procurement department while the status of purchasing can be flagged and tagged back to the element database by the procurement department to make it visible for Design Drafting and PM Department. The key objective is the use of automation in the creation of PR documents directly from BOM developed in BIM design authoring tool to reduce or eliminate human errors and bring consistency to the different reporting formats for material take-offs. The whole process and workflow in BIM design authoring tool and stand-alone software are presented in Fig. 7-11.

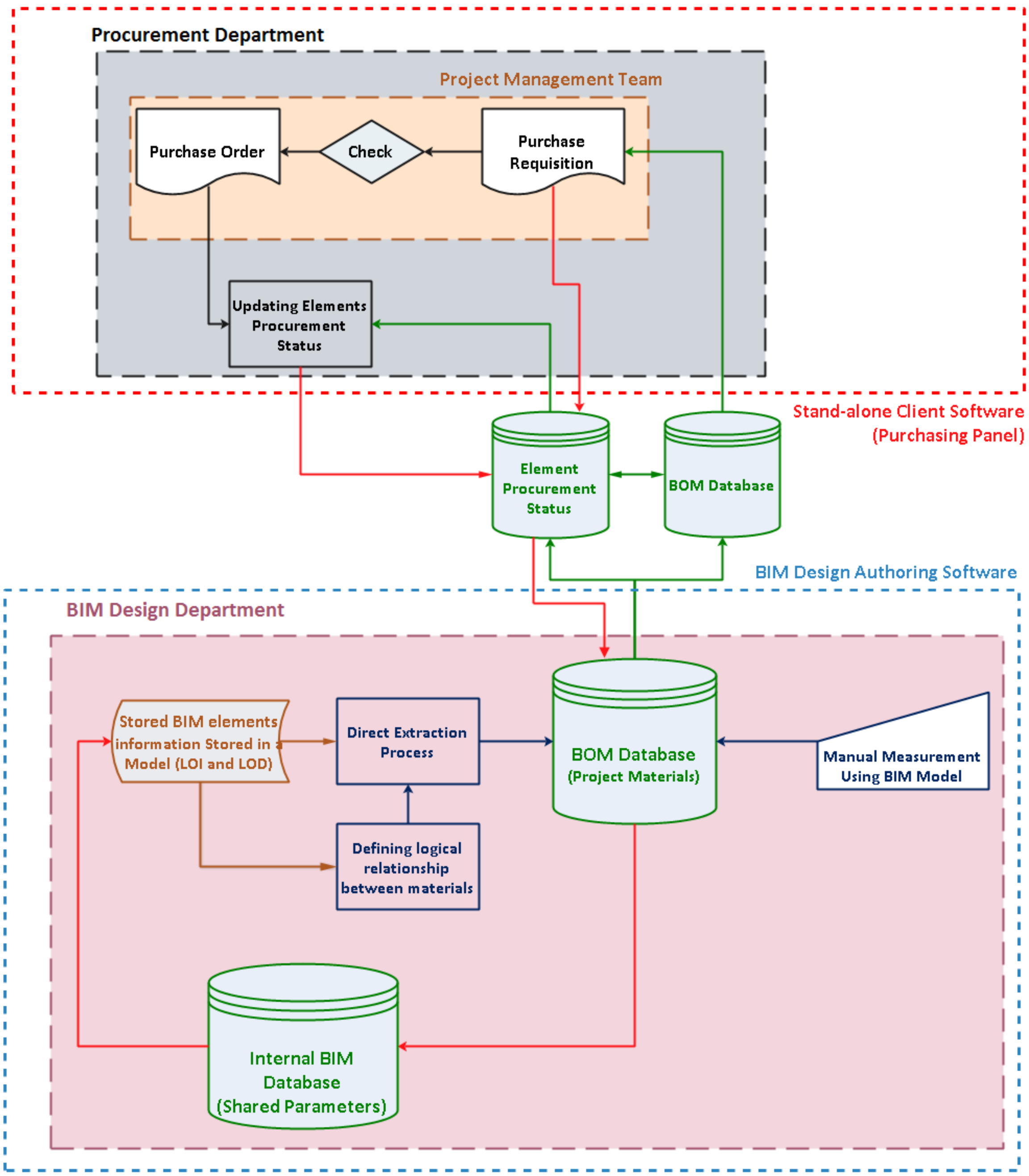

Fig. 7-11 - The proposed 5'D comprehensive process map and workflows

The proposed comprehensive 5'D BIM system coordinates the procurement process and allows the visualization of the purchasing progress back in the BIM environment for design drafting department. This approach should address most of the difficulties listed in Table 7-1. Problem a) regarding the human errors in converting BOM reports to PR is eliminated as the PR document will be produced directly from digital BOM records in the BIM database. Likewise, the purchasing status of a specific element in the WBS is captured in the BIM system (stored as shared parameter). To help enforce company processes regarding design changes that would affect purchasing activities revision control processes could be applied on each data handover. This approach would support proper monitoring and reporting capabilities and thus address problems b) to d) in Table 7-1. The automation and monitoring of the process would help overcome any inertia in developing of PRs by the design drafting department and having the procurement department perform its checks (final material description and information checks) will address issue e) in Table 7-1.

This proposed process will require some development and modification of both the procurement and the BIM systems. However, the development of stand-alone software as a monitoring portal panel for the procurement department was proposed, using an off-the-shelf database that could be subsequently loaded into ERP system, like SAP's ERP, (through an API, import or transfer by Excel sheets). To create a visualization of the procurement status in the BIM system would require the states of the materials in WBS be linked to some parameters in the 3D model elements, which could then be filtered for or highlighted using the BIM GUI (interface).

7.5 Demonstration and Evaluation process through an example PEB project

7.5.1 BIM based software and Stand-alone Purchasing Portal

A PEB design tool was developed using the Autodesk Revit GUI to interact with users and automate the design and modeling processes of a PEB building. This tool implements automated architectural model development and structural analytical model development using pre-designed PEB structural and non-structural Autodesk parametric 3D objects (families) based on user input. Further details are available in ([25]-chapter 2 of this thesis). Here, only results related to evaluating the impact such a system has on the application of MTO in 5D and 5'D BIM applications are presented.

To do this, a stand-alone portal (client Windows Application Program) software was designed and developed to evaluate the communication performance of the proposed 5'D system with a purchasing department. The evaluation used an example PEB project. The software interfaces are presented through snapshots and illustrations of their processes in following sections.

7.5.2 Example PEB project

The example project was a real industrial PEB building that had been designed and developed initially using a traditional non-BIM system. The design of this 21m x 16m x (11.53m Eave Height) Gas Compression Station was initially done in the absence of any BIM model for PEB structures, the building enclosure, or a collaborative environment. As it is shown in Fig. 7-12 (top center), the building owner and general contractor developed comprehensive BIM models for all mechanical and electrical components. Note that the rough 3D enclosure model that is shown in Fig. 7-12 (in grey, top right), is a low LOD CAD conceptual model developed by the owner to describe the required building and had no value for design in later steps. The main design automation user interface, added as a Ribbon to the Autodesk Revit GUI and the output BIM model (the outcome of the automated BIM model development processes) are shown in Fig. 7-12 as well (middle and bottom of the figure respectfully).

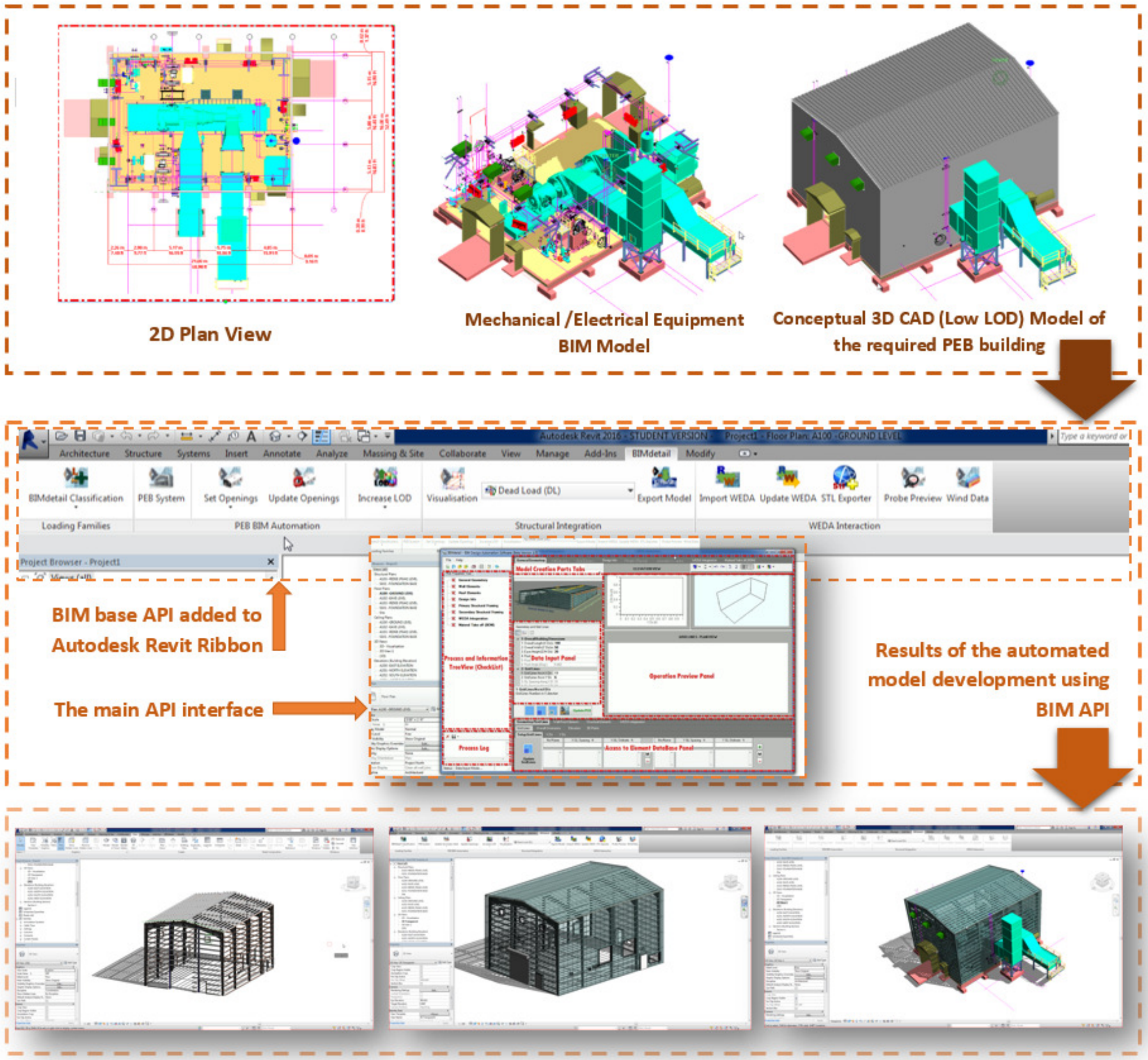

Fig. 7-12 - Example Project with existing BIM model for all the mechanical/electrical building components but the PEB structure and building enclosure ([25]-chapter 2 of this thesis)

7.5.3 Automated MTO and 5'D BIM coordinated system/process demonstration on developed software

The initial automatically developed models achieved the desired LOD300 (suitable for initial cost estimates) but need further development for actual procurement activities.

To deal with changing WBS and to monitor MTO related issues of each component the main material definition panel was developed as shown in Fig. 7-13. The interface allows for the cost related information such as units, waste percentage and type of take-off to be defined for high-level WBS at any model development stage (shown in Fig. 7-13). Most importantly, the logic of relationship, ratio and the related main material to be quantified is defined for in this panel to support the semi-automation process for remaining materials take-off.

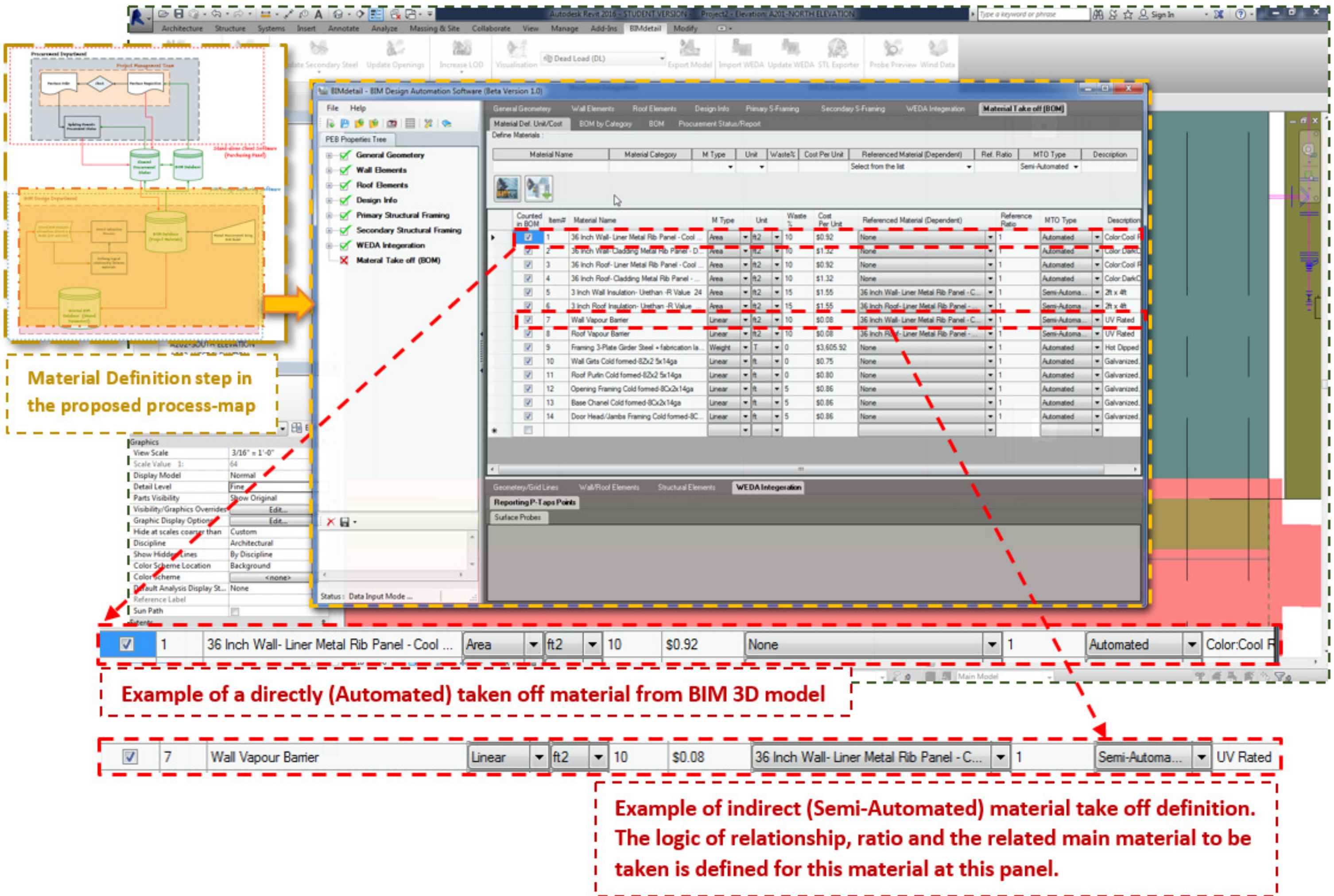

Fig. 7-13 - The main API panel for definition of material cost properties and take-off method (Automated, Semi-Automated Manual)

As mentioned earlier, in order to cover 100% of materials in the project in MTO processes, some remaining materials need to be accounted for using BIM-assisted manual take-off processes. This operation is performed using 2D/3D BIM snapping helpers, BIM 2D/3D views for visualization of the take-off processes and automated math operations (adding up all the quantities in one operation). This procedure, including required steps and the results for an example material in example PEB project is shown in Fig. 7-14

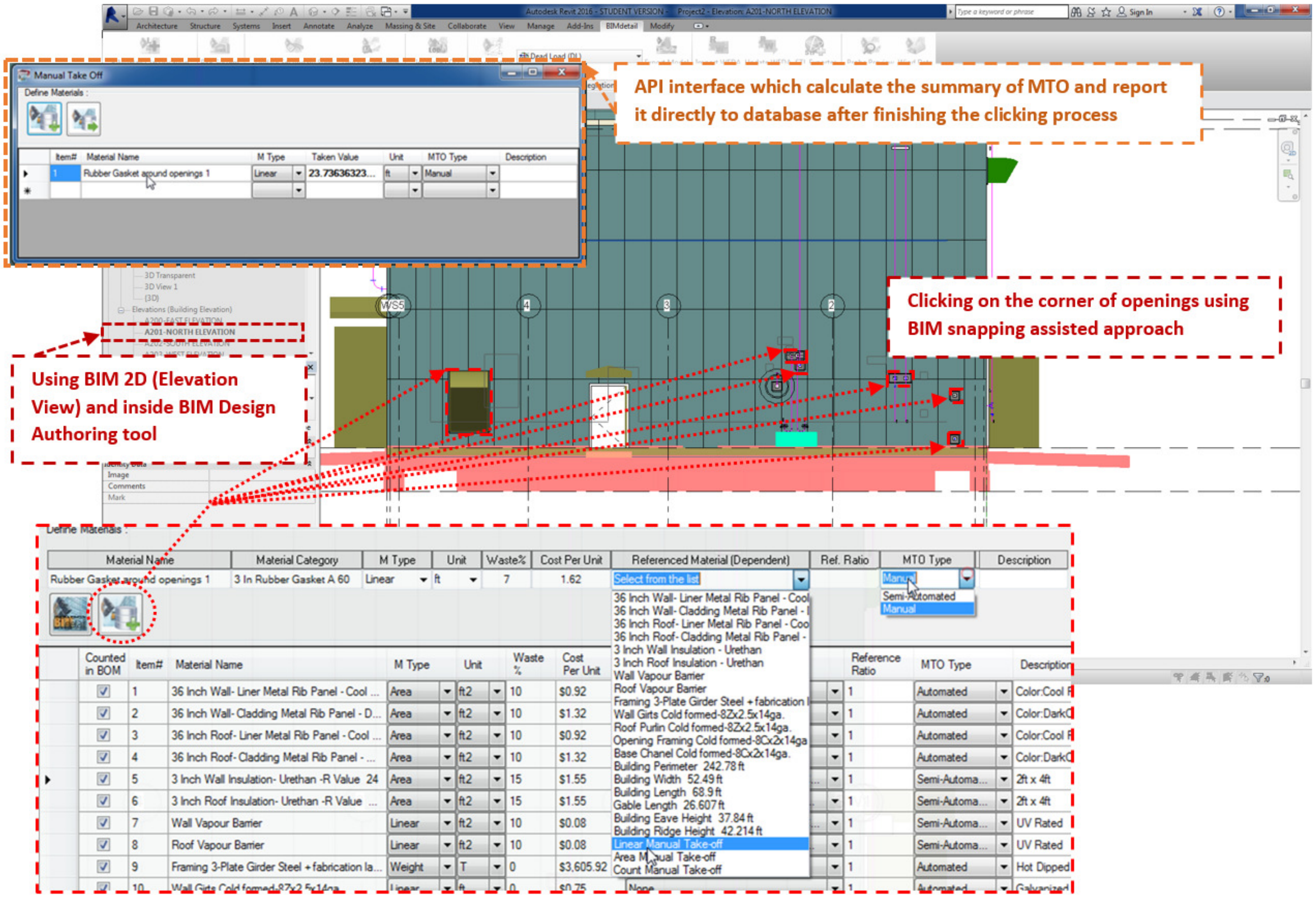

Fig. 7-14 – Illustration of the BIM-assisted manual take-off procedure, required steps and the results for an example material in example PEB project

The list of all materials in the project (BOM) in WBS breakdowns is generated after material definition step for the higher-level WBS.

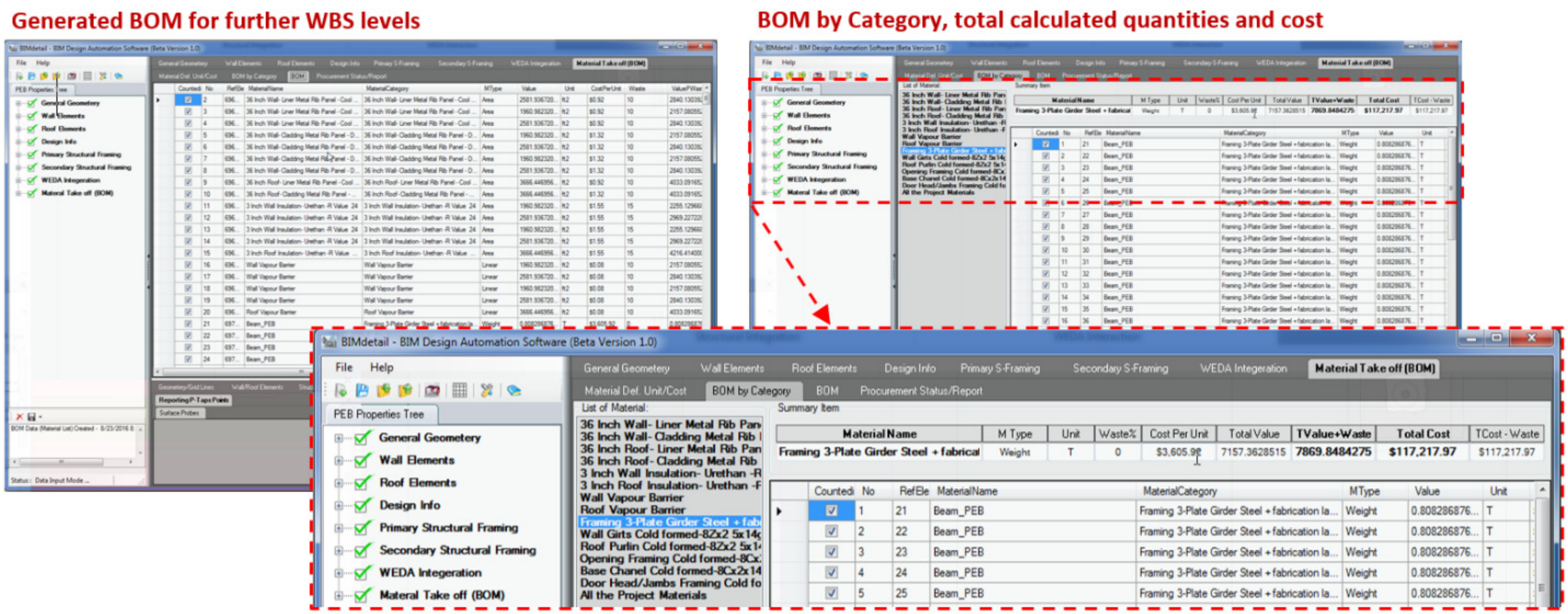

Fig. 7-15 - Automatically generated BOM for the further WBS levels and cost estimation of the project materials by category using a comprehensive 5D/5'D BIM system (results)

The results of cost estimation and material quantities in (detailed BOM list), are accessible to the BIM designer before handing over to the purchasing department. Therefore, the Design Drafting department can check and monitor the cost and details before any PR document is created. The results of a successful completed 5D/5'D BIM modeling is presented in Fig. 7-15.

After a final check on BOM by design drafting department, a list of materials in a higher-level WBS in conjunction with their purchasing status (Revision) id created. Fig. 7-16 illustrates the process of automated purchase requisition document creation from the BOM database inside the BIM design authoring software.

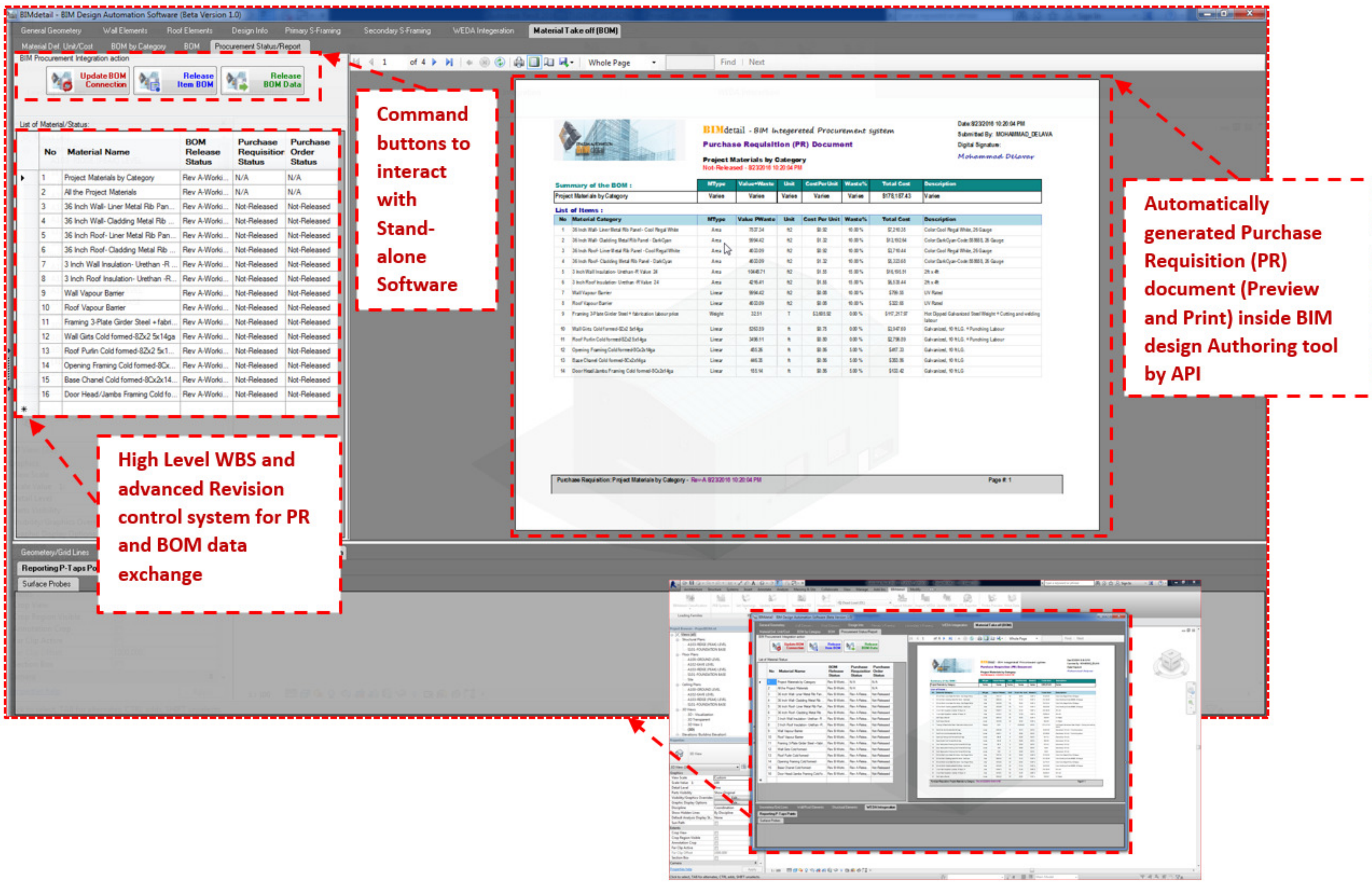

Fig. 7-16 - Automated Purchase Requisition (PR) generation process inside BIM design authoring tool using API

The electronic Purchase Requisition information is saved, and the database is updated. It is then handed over to the purchasing department. A very similar interface was developed for the purchasing department to use to import the purchase requisition information and to update the purchasing status. After the use of project management approval functionality (the stand-alone software can be loaded by PM department as well), the purchasing department can transfer the PR information into an ERP system and indicate the process of Purchase Order creation as “proceed” in the stand-alone software. The Revision/status of the updated material is automatically updated in the database as well. The stand-alone purchasing panel software is illustrated in Fig. 7-17.

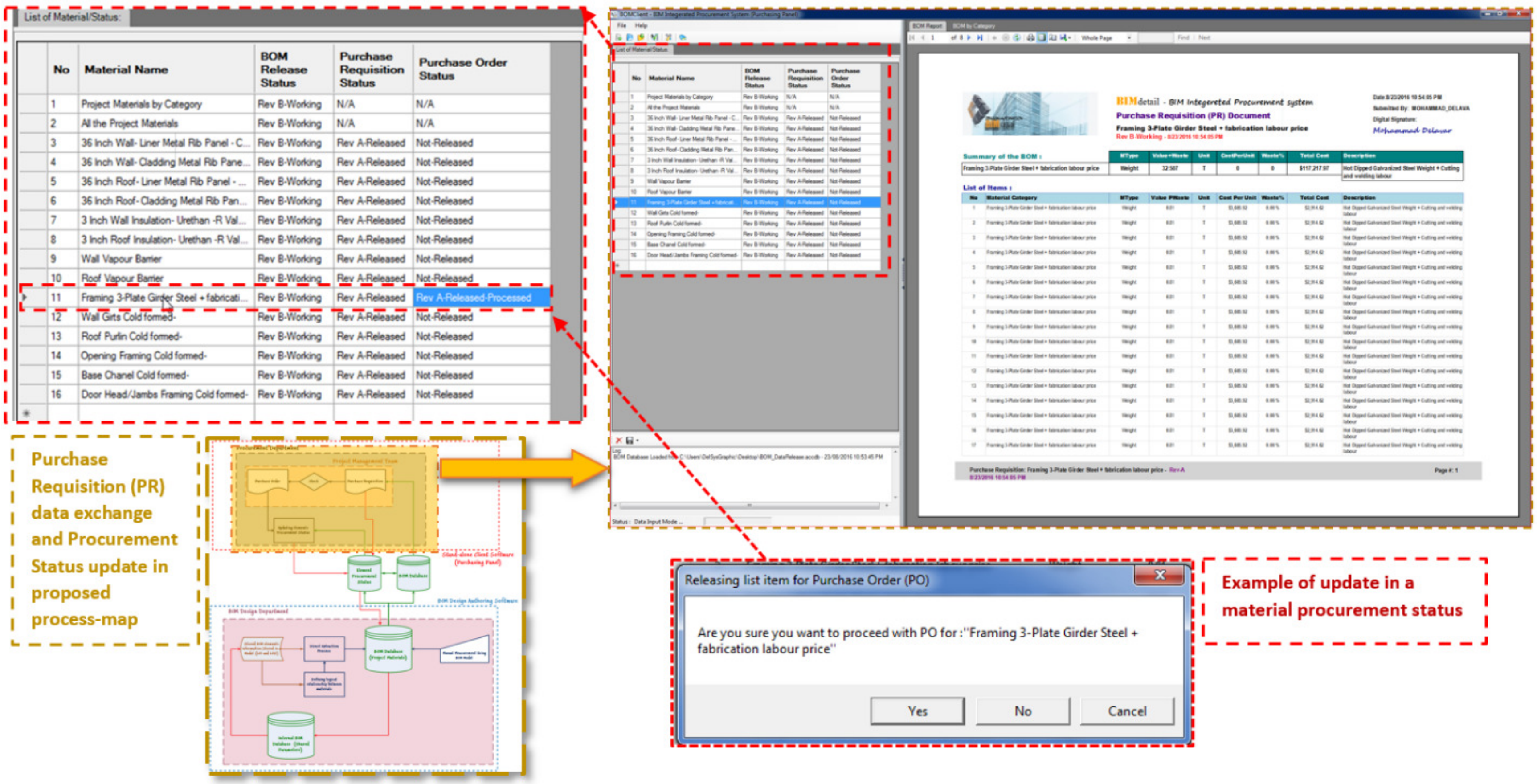

Fig. 7-17 - Stand-alone purchasing panel (WAP) software interface and an example of updating procurement status of an element

Eventually and by updating the procurement status of materials in purchasing department, the main BIM database is also updated. Therefore, by performing the update process inside the BIM design authoring tool, the design drafting department can get access to updated procurement status automatically. Using 3D visualization capabilities inherent in BIM, added shared parameters are updated and presented in right in the BIM design authoring interface (in a properties window). The process of viewing the 5'D BIM modeling for an example building element(s) with an updated purchasing status in the last step in the stand-alone purchasing software is illustrated in Fig. 7-18.

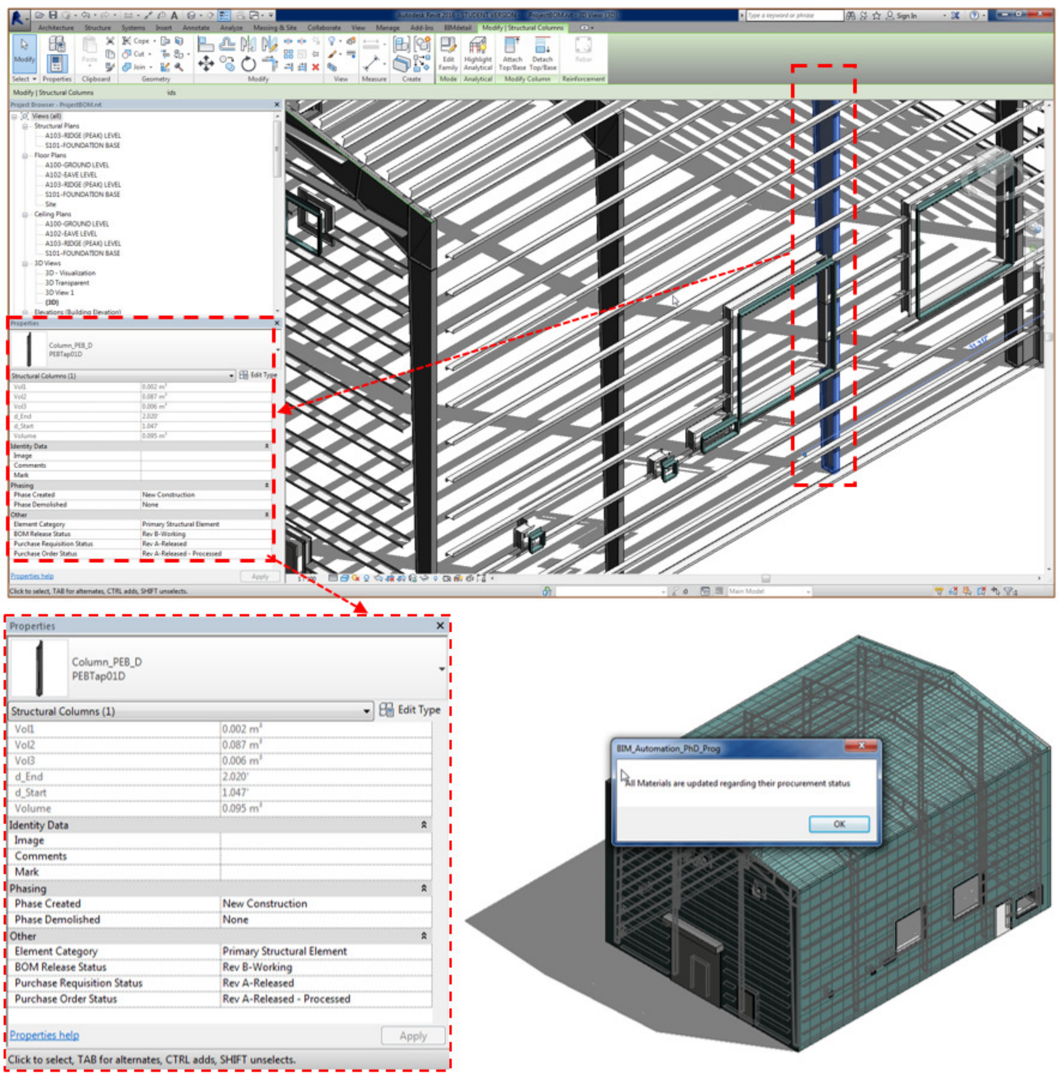

Fig. 7-18 - BIM Visualization for 5'D modeling - addressing the updated status of the procurement of the example material after operation in stand-alone software

7.5.4 Results and Discussion

Review of the test case results revealed that the initial model level of development (LOD 300) made it possible to take-off around 80% to 90% of the building materials automatically. Furthermore, complete material take-off was achieved with the application of the semi-automated and manual take-off approaches, similar to current procurement practices. Importantly, these semi-automated and manual take-off activities were only necessary on a greatly reduced portion of the design and thus required a similarly reduced effort. The developed BOM inside the BIM design authoring software was then successfully used to generate PRs and handed off to the procurement department after appropriate management approvals. The example above also illustrated the process of updating the status of procurement of the materials for access in the BIM design environment (illustrating a 5'D BIM model). In conclusion, the whole process for 5D and 5'D BIM modeling was successfully followed for the example PEB project.

Conclusion

This paper presented an integrated systems approach (based on automated BIM modelling) to addressing many of the existing inefficiencies in current BIM-based cost estimation systems. This was done both for early estimation, supporting 5D BIM modeling, and later for developing PR (termed 5'D modelling). The approach used the logic of relationship between the modelled project materials combined with some manual BIM-assisted quantification. The need for interaction between designers, management, and people in procurement required the proposed system to provide information and get input from all three stakeholders.

To demonstrate the feasibility of the approach the system was implemented on top of an existing PEB design automation research platform and in a stand-alone purchasing requisitions management tool. By doing this some of the advantages of this BIM-based system such as visualization and improved decision-making ability were illustrated for an example PEB project.

Also worthy of note is that any automated BIM-based construction design process could be used as input into the procurement process and systems described. This means other domains, like Pre-Fab construction could also benefit from this work in the near future and, potentially later, the general construction industry could benefit depending on the degree of adoption of automation in design detailing.

Acknowledgement

The authors would like to show their gratitude to Stephen Hudak of Varco Pruden Building (VP) and the rest of VP's crew, upon whose substantial supports this research was based.

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Chapter 8

8 Conclusions and Recommendations

This chapter outlines the conclusions of the study and makes some recommendations for future work.

8.1 Conclusions

The impact of this thesis should be considered from both a general perspective of creating an automated BIM-assisted design system for the PEB industry and in terms of specific achievements and contributions towards realizing a BIM framework and implementation for the PEB design and construction sector.

8.1.1 General conclusion

This research successfully met its general objective of conceiving and creating an automated BIM-assisted design system for the PEB industry. To achieve this, a BIM framework, workflows/process maps and data-exchange strategies for the PEB industry had to be developed to sufficient maturity to be implemented in software and followed to deliver successfully an industry-sourced PEB design project. By doing this, it demonstrates that PEB design and delivery processes can be based on BIM workflows and tools that enable better integration and interoperability with other design, engineering and procurement stakeholders and their processes. These benefits directly address one of the significant limitations of current PEB processes of having to invest the expert resources and time to do significant manual rework or analysis to address any project requirements beyond delivering routine structures. This was illustrated by using BIM technology to integrate tools for the domains of wind engineering and MTO.

As part of this work, the current ROI implications of selecting different model LOD requirements was reviewed based on industry practitioner assessments. It was concluded that an LOD of 300 is a broadly good, if not optimal level for model development, thus providing a useful LOD guideline to the broader construction industry currently using BIM. That said, it was observed that significant resources are required during design to reach those LODs and that the automated design development processes common to the PEB industry could be applicable in the broader context. Use of such automation has the potential to improve further the ROI achieved when working with LOD 300 models. The feasibility of automated design development was directly illustrated for the PEB context through implementation and the PEB case study example.

Overall, the outcomes show a significant capability to improve the time and cost efficiency of the PEB design system, as well as its flexibility, through the switch to a BIM technology foundation and the application of automation in design, analysis and procurement activities.

8.1.2 Specific achievements and conclusions

The following are specific achievements and conclusions of this research.

1. The main non-technical challenge for the application of BIM in the PEB industry comes from its 'single source responsible construction' business model. The main technical challenges are interoperability issues that arise due to the sector's custom design software and use of customized construction elements. To add to these challenges are some potential legal and contractual issues, including the potential exposure of IP. Some of the flaws and weaknesses of the current PEB processes that were identified included an increase in the change order costs and lack of 'project coordination' capability and versatility. Full utilization of the Prefab process for the PEB sector was observed to be inappropriate due to a lack of design automation and optimization.
2. New BIM processes, project collaboration workflows/process maps and data-exchange strategies were developed and put into a proposed BIM framework for PEB industry and illustrated in this thesis. An example PEB project was followed through the proposed workflow illustrating its value. The main technical challenges in developing a BIM framework for PEB industry were identified to be; preserving design automation while allowing for design customization within a BIM system, shifting between LOD levels to support design, and achieving interoperability with other tools. In particular, a "Planar Concept" and "Floating LOD" approach were developed to address issues preventing the use of automation in the PEB design development.
3. A software application was developed and evaluated to assess the feasibility of the approach and algorithms proposed by the proposed BIM framework for PEB. The

results indicated a significant improvement in the project collaboration quality and design development time and cost. The BIM framework and associated concepts developed were also observed to support improved collaboration between different disciplines in the design of a PEB projects by simplifying or enabling model and analysis information exchanges.

4. By relating LODs to various industry applications of BIM and their associated ROIs and benefits, it was possible to develop a couple of curves that show that a LOD of 300 is a broadly good, if not optimal level for model development considering the trade-offs of benefits versus costs for the general construction industry. It was also observed that currently most BIM users only develop BIM models to LOD200 which is short of the identified LOD300, probably limiting the potential ROI for their projects. Analysis of the data also showed that current BIM technologies and user's ability to handle highly developed models while performing design and analysis tasks contribute to the lower ROIs experienced when working with higher LOD models. If these challenges could be overcome, higher LODs and commensurately more advanced BIM applications (reuse of the models) would become worthwhile in terms of ROI.
5. The PEB approach for modeling and designing architectural and structural models simultaneously was adapted for automation and deployed in a BIM modeling environment. By classifying building elements to indicate if they had a structural role and by using intelligent building element models, the automated BIM software was able to shift the design model between LODs to support different uses without manual editing. This was introduced as the floating LOD concept. A Planar Concept was also introduced to provide a link between and simultaneous development of the design's structural elements and their analytical analogs. The result was the effective integration of the structural analysis of the design as part of the process.
6. A detailed process map was developed defining data exchange strategies and the application of a "central database" to deliver integration between BIM design and Wind Engineering, for both wind tunnel and CFD based approaches. The implementation of this required establishing a unified referencing coordinate base system for setting probe positions and reporting probe values and the generation of tessellated models for communicating with CFD tools. The results showed the developed mechanisms

supported the desired data exchange processes and were successful in providing an integrated BIM-based design and CFD analysis environment. Also, the flexibility and ease of the integrated system were observed to have the potential to significantly reduce the cost of the design process by reducing geometric modeling times during wind evaluation activities, and extending the number of engineering disciplines that can collaborate on designs.

7. Cost estimation is a big part of the PEB process. An integrated systems approach (based on automated BIM modeling) to addressing many of the existing inefficiencies in current BIM-based cost estimation systems was developed. This was done both for early estimation (i.e. 5D BIM modeling), and later for developing purchase requisitions (termed 5'D modeling). The results demonstrated that interactions between designers, management, and procurement could be facilitated and documented by using the BIM design model along with defined logic for non-modelled project materials and some BIM-assisted manual quantification. Evaluation of this on the testbed illustrated significant benefits of improved visualization and accuracy of BOM on the ease of making decisions during procurement tasks.

8.2 Recommendation for Future Research

The current thesis discusses challenges and required development for creating an automated BIM-assisted design system for PEB industry. The following future research topics are suggested as an expansion of this research, particularly in support of extending the application of these results to other, more general, construction domains:

- Examination and evaluation of design development automation in support of the Pre-fabrication industry. A similar approach using the "Planar Concept" could be applicable for more conventional buildings composed of larger designed systems that are progressively refined into smaller components. Investigation along this line could improve the efficiency of the Pre-fab sector design processes and reveal ways the approach could be further generalized to the general construction sector.

- Examination of the "Floating LOD" for system families (e.g., wall/ roof assemblies) of conventional buildings which are less constrained than those encountered in the PEB sector would allow for more complex shapes and sizes of buildings to be designed more efficiently.

- Based on a successful numerical analysis to find a broadly optimum LOD, there would be value in extending the survey base, e.g. through BIM international sectors such as buildingSMART, NIBS, and CanBIM, and applying further analysis. One prospect would be to review the practical experience of international projects with a level of BIM LOD vs. the achievement of project goals and drivers. If sufficient information could be gathered, reviewing the LOD related ROIs experienced along alternate procurement and construction domain lines (e.g., pre-fab, post construction, commercial, residential, non-PEB industrial, high/low/mid-rise, etc.) and disciplines (e.g. structural, mechanical, electrical, etc.) could yield valuable insight into the strengths and weaknesses of each. This could be used to develop and progressively update specific guidelines for preferred LOD and BIM model usage relevant to individual project contexts. Consequently, it could end up encouraging the expansion of BIM implementation across the larger construction sector.

- Given the ability to automatically develop CFD models, including horizontal and vertical openings, from BIM models already established by this work, further investigation is possible to support improvements in how designs take into account airflow and heat/moisture transfer inside and in and out of building envelopes.

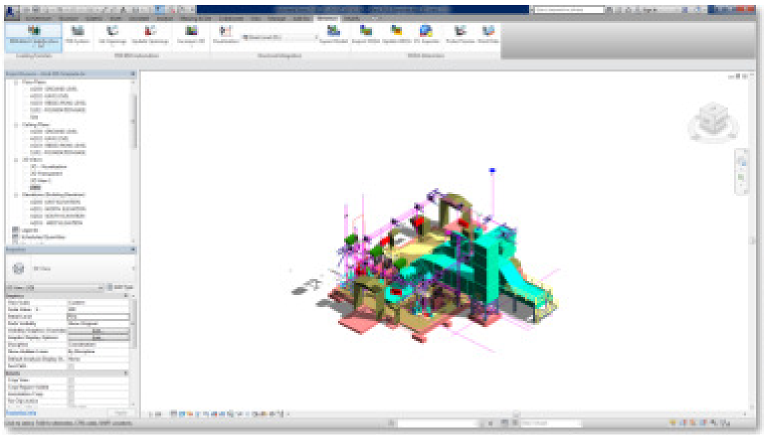
- Similarly, the ability to generate and integrate CFD models and analysis, with façade elements incorporated and removed, would support continued research on different façade failure scenarios and the subsequent behavior of the building. Work on this could lead to new building codes, new risk assessment scenarios and even the optimization of individual designs for wind event resiliency.

- The pre-fab construction sector has quite similar in a number of ways to the PEB industry sector. Its reliance on models to drive its design and procurement processes suggest it would be natural subsequent target for applying the approaches developed to integrate the design and procurement activities in this thesis. Other areas of construction that make use of automation or design decomposition, such as modular construction, could also benefit.

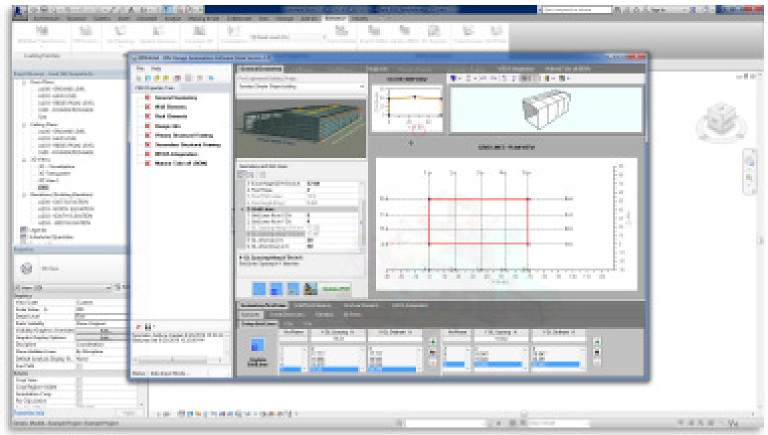
Appendix

A. A sample of Codes developed for API Software in Visual Basic.Net

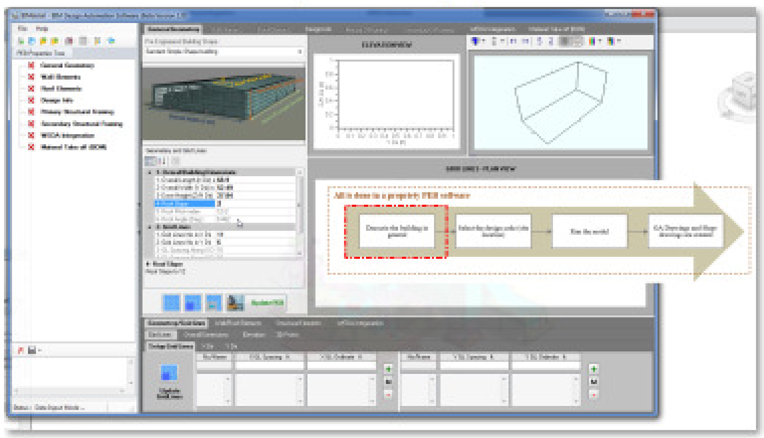
Please see the electronic attached snippet/code file, as a sample of Advanced Visual Basic.net class library (.dll) program, developed in this research for implementation of BIM in PEB and automation in its BIM design processes. The coding was developed to create an API software which uses Autodesk Revit SDK for BIM model-authoring and manipulation. The attachment is only a small portion of the whole API software which automates the model development process of a simple (four walls, simple two pitches) PEB building. The Software interface and the steps which code performs are illustrated in following figures:



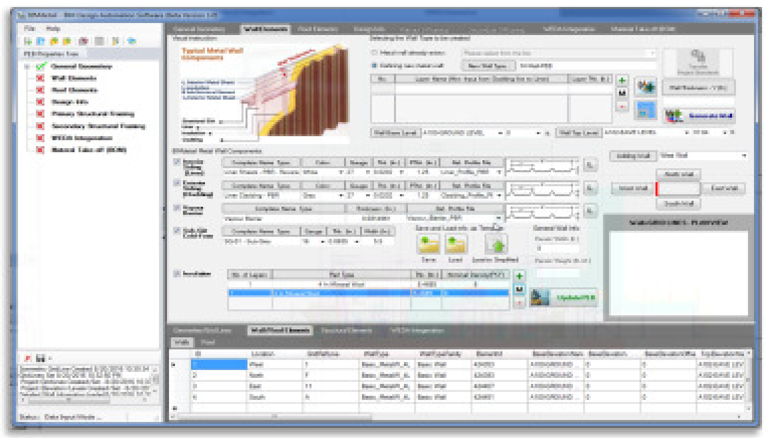
STEP 1: Starting the design process on a collaborative environment and Building the PEB 3D model on Existing BIM models of Mechanical/Electrical equipments



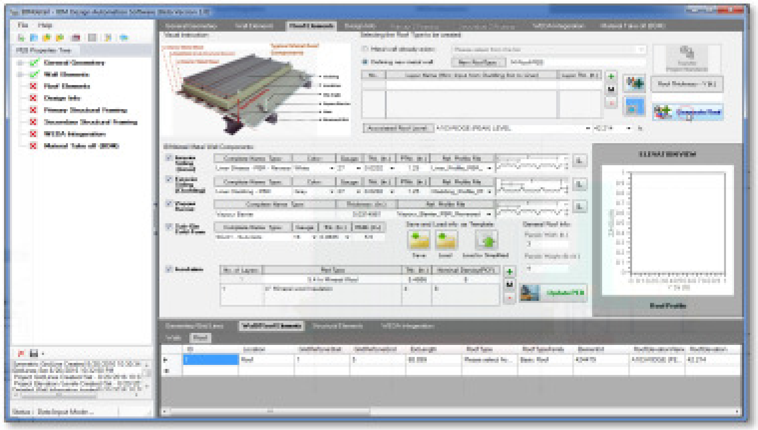
STEP 2: Loading the API software on Autodesk Revit GUI

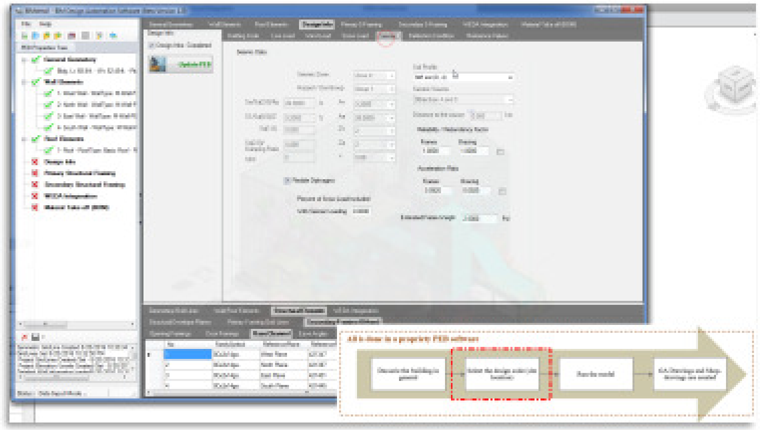


STEP 3: Describing the PEB building by inputing the geometry properties and building Grid lines



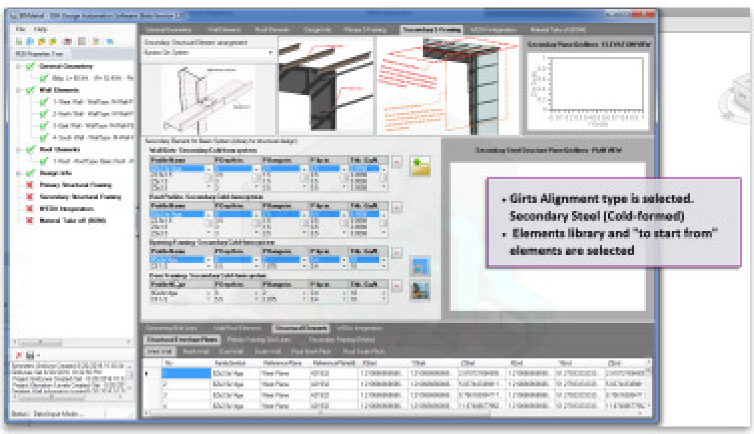
STEP 4: Inputting/Loading/Saving PEB wall system properties The input information at this step can increase LOI of the BIM model to be used later on using "Floating LOD" concept

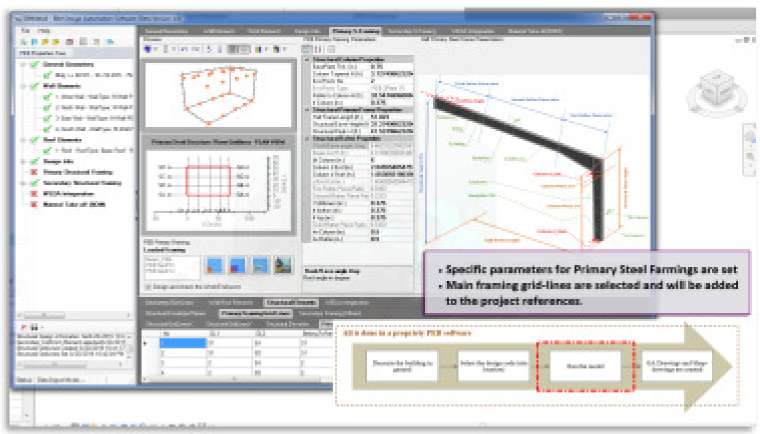




STEP 5: Inputting/Loading/Saving Roof system properties. The input information at this step can increase LOI of the BIM model to be used later on using "Floating LOD" concept

STEP 6: Structural Design criteria and specifications are input at this stage for internal structural design process





STEP 7: Secondary structural elements design criteria is input here using the BIM structural components loaded in Revit

STEP 8: Primary structural elements design criteria is input here (different manufacturer can customize their main frames at this stage

B. *High Level list of Project issues reported in the case study PEB project*

ASSOCIATED COSTS WITH DESIGN/DRAFTING ISSUES AND PROBLEM DUE TO USING 2D BASE - NON-BIM - SYSTEM (NCR REPORTS)						
NO.	**Referred Issue**	**Cause of Occurrence/ How BIM process could provide solution**	**Associated cost to cover damage**	**Equivalent Designer/Drafter Resource usage (Hrs.) Average $25/hr.**	**NCR#**	**Reported Date**
1	**Eave Details**	Materials designed and supplied to the site with incorrect size/shape/material. 2D Architectural details do not match the 2D Structural Design (details) - Using Generic 2D architectural details	**$1,251.68**	51	**002**	**12-Aug-2013**
2	**Incorrect Flashing**	Materials designed and supplied to the site with incorrect size/shape/material. Flashing profile drawings have been designed based on 2D Non-BIM generic architectural details	**$4,374.07**	175	**009**	**15-Aug-2013**
3	**Incorrect Flashing**	Materials designed and supplied to the site with incorrect size/shape/material. Flashing profile drawings have been designed based on 2D Non-BIM generic architectural details	**$2,022.25**	81	**008**	**14-Aug-2013**

4	**Overhead Details flashing**	Materials designed and supplied to the site with incorrect size/shape/material. Flashing profile drawings have been designed based on 2D Non-BIM generic architectural details	**$708.00**	29	**012**	**15-Aug-2013**
5	**Incorrect Flashing size**	Materials designed and supplied to the site with incorrect size/shape/material. Flashing profile drawings have been designed based on 2D Non-BIM generic architectural details	**$1,375.67**	56	**010**	**15-Aug-2013**
6	**Structural Fabrication Drawings**	Materials designed and supplied to the site with incorrect size/shape/material Structural Fabrication Drawings for Zee/Cee girts has been designed/drafted using 2D CAD drawings	**$2,400.00**	96	**016 (1/2)**	**27-Aug-2013**
7	**Structural Fabrication Drawings**	Materials designed and supplied to the site with incorrect size/shape/material Structural Fabrication Drawings for Zee/Cee girts has been designed/drafted using 2D CAD drawings	**$2,800.00**	112	**013**	**15-Aug-2013**

8	**WT Interference**	Site Retrofit of Secondary elements required due to a clashing occurrence. Secondary structural elements (fabrication drawings) have been designed without incorporation with a 3D BIM model of primary elements. No BIM automated or semi-automated clash detection has been performed.	**$10,000.00**	400	**014, 015, 016 (1/2)**	**14-Aug-2013, 15-Aug-2013, 27-Aug-2013**
9	**Incorrect Purchase order info**	Purchase Order missed or supplicated. (Procurement has not been performed in a BIM base Procurement has not been performed in a BIM base system. A BIM base system includes a collaborated package of BIM automated material quantity takeoff, purchase requisition (Bill of material) and Purchase order which makes a trackable workflow between design/drafting department, project management, and procurement department).	**$2,521.00**	101	**018**	**26-Aug-2013**

10	**Incorrect clips**	The color of structural elements as information has not been attached to 2D/3D structural fabrication drawings. Materials arrived at site with incorrect color. (BIM attaches all required information to designed models so that it can be shown on any outputs of model or drafts or reports. In this case information of elements never gets lost in the process of the project between disciplines)	**$6,220.75**	249	**011**	**15-Aug-2013**
		In total:	**$33,673.42**	1350	Hrs.	

- This table is a very high level report and items reported in the above tables are summarized in 10 different items, due to some confidential restriction. Detailed list included over 50 different reports.

9 Curriculum Vitae

EDUCATION

- **Master of Engineering (M.Eng.),** Civil and Environmental Engineering Department, research project on "Improving High Alumina Cement Conversion Occurrence Using Nano-Materials", Western University Canada (formerly known as "University of Western Ontario"), London Ontario, Canada, 2011-2012
- **B.Sc. of Engineering,** Civil and Environmental Engineering, Azad Islamic University, Mashhad, Iran, 2004-2008

HONORS & AWARDS

- **2014: Natural Sciences and Engineering Research Council of Canada (NSERC) IPS Scholarship**, Industrial Postgraduate Award/Scholarships for research on construction management and BIM Technology development.
- **2012-2016: Western Graduate Research Scholarship (WGRS),** School of Graduate and Postdoctoral Studies, Western University Canada, Granted for four years of the Ph.D. research program (eight terms).
- **2013:** Nominated for **Ontario Graduate Scholarship (OGS)** Ministry of Training, Colleges/Universities, ON, Canada
- **2008: Student Rank #1** for outstanding performance in semester GPA (17.32/20), undergraduate studies, CEE Dept.
- **2008:** Awarded for designing and developing user-friendly software for structural analysis using "KANI" and "Moment Distribution Method", the annual scientific achievements fair, provincial fair by the "Ministry of Education", Mashhad, Iran

ACADEMIC/SCIENTIFIC ACTIVITIES:

COURSE DEVELOPMENT:

2015: ENGSCI 9510 CEE, "Engineering Planning and Project Management", an online course, association in online course development for civil engineering department with Kevin McGuire P.Eng. (Instructor), Western University Canada

RESEARCH TEAM DEVELOPMENT:

2007-2009: "Water Resource Management Research Unit", Association in research team development, development of the online/cloud base study with Dr. F. Kham Chin, Islamic Azad Islamic University of Mashhad

JOURNAL EDITORIAL POSITION:

2010-2013: "Green Building (Sakhteman–eSabz)", (scientific journal)/A Bimonthly Journal of Building Industry, editorial committee member, Mashhad, Iran,

SOFTWARE DEVELOPMENT:

- **2015:** Designing & developing Autodesk Revit API software, BIM design automation and net base BOM and 5'D BIM procurement management, I.P. Shared with ATCOEM and Western University Canada
- **2011:** Designing & developing user-friendly software to study numerical method in obtaining the response of structure to earthquake, "Advance Seismic Design" (academic /course project), Western University Canada
- **2008-2010:** Designing & developing user-friendly software to design/analysis the column base plate connection under the biaxial moment/seismic loading using direct import from CSI ETABS/SAP2000 (commercial software)
- **2009:** Designing & developing user-friendly software to develop the Interaction diagram of reinforced concrete columns, "Concrete Structure Design II" (academic /course project), Islamic Azad University Mashhad, Iran
- **2008-2009:** Designing & developing two user-friendly structural analysis software using "Kani" and "Moment Distribution" methods, "Structural Analysis II" (academic /course project), Islamic Azad University Mashhad, Iran

- **2007:** Designing & developing user-friendly software for “Uniform Flow” calculation, “Open Hydraulic Channel Design” (academic /course project), Islamic Azad University Mashhad, Iran

UNIVERSITY INSTRUCTION/TEACHING ASSISTANCE:

2012-2016: Civil and Environmental Engineering Department, Western University Canada:

- CEE 9518b: “Building Information Modeling.”
- CEE 9510: “Engineering Planning and Project Management.”
- CEE 3369b: “Materials for Civil Engineering.”
- ES4498G-001: “Engineering Ethics, Sustainable Development and the Law.”

2009: Civil and Environmental Engineering Department, Islamic Azad University of Mashhad: **“Hydrology and Water Resource Management,”** as Dr. F. Khamchin’s assistance

SEMINARS/CONFERENCES (AS PRESENTER):

- **2016: “Discussion on BIM Implementation in Pre-Engineered Building (PEB) Industry”,** CSCE Annual Conference. 2016 - June 1-4, Canadian Society for Civil Engineering, London, ON, Canada, 2016
- 2012: “Revolution in Cement Technology - Study on Conversion Prevention of High Alumina Cement,” Civil Eng. Dept. seminar series, April 2012, Western University Canada, London, ON, Canada
- **2008:** “A Review on the Challenges on Mashhad Water Supply System using “Dusty” Dam Conservation,” Mashhad water resource management conference, Nov-2009, Islamic Azad University of Mashhad, Iran

PUBLICATIONS

BOOKS

- **2015-2016: Canadian Practice Manual for BIM**, member of authoring committee, contribution in authorship of “Vol.3-Ch.3- LOD Implications”, buildingSMART Canada-The Institute for BIM in Canada (IBC)

- **2008-2013**: Farhad Khamchin, Mohammad Delavar, Danial Reza Zadeh, **Dictionary of Civil Engineering, Water and Environmental Sciences (English/Persian)**, First, Talab, Mashhad, Iran, Page1-236, ISBN: 978-600-93745-4-0. DOI:553-03. Published on 2013 Dec 15th. The most expanded English/Persian dictionary in Civil Engineering, Hydrology and Environmental Sciences. Submitted for review to editorial in 2009

PUBLISHED MANUSCRIPTS

- **2016:** Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **Discussion on BIM implementation in Pre-Engineered Building (PEB) industry**, in CSCE Annual Conference. 2016 - June 1-4, Canadian Society for Civil Engineering, London, Ontario, Canada, 2016: pp. 1–10.
- 2009: Mohammad Delavar, Advanced Moderate Bracing System using Reinforced Concrete Armed by Steel Fibers for High- rise/Seismic Sensitive Buildings –A Literature Review, May-Jun 2009, Vol3 No15, ”Green Building (Sakhteman – eSabz),” A bimonthly scientific journal of building industry
- **2009:** Mohammad Delavar, **Ductility and Durability of the Self-Healing Concrete, –A Literature Review**, July-Aug 2009, Vol3 No16,”Green Building (Sakhteman–eSab),” A bimonthly scientific journal of building industry
- **2009:** Mohammad Delavar, **Evaluation of Implementation of Project Management Approaches on High-Rise Construction Projects in Iran** Nov-Dec 2009, Vol3 No18,”Green Building (Sakhteman–eSabz),” A bimonthly scientific journal of building industry

PREPARED FOR SUBMISSION

- 2016: Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **Benefits, Risks and Challenges in BIM implementation for Pre-Engineered Building (PEB) Industry**, London, ON, Canada, 2016.
- 2016: Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **Building Information Modeling (BIM) framework for Pre-Engineered Building construction projects**, London, ON, Canada, 2016.

- 2016: Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **BIM Optimal Level of Development (LOD),** London, Ontario, Canada, 2016.
- 2016: Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **Automation in Building Information Modeling (BIM) process; An example Pre-Engineered Building Project**, London, Ontario, Canada, 2016.
- 2016: Mohammad Delavar, Girma T. Bitsuamlak, John K. Dickinson, **Automated BIM-based Process for Wind Engineering Design Collaboration; An example Pre-Engineered Building Project**, London, Ontario, Canada, 2016
- 2016: Mohammad Delavar, John K. Dickinson, Girma T. Bitsuamlak, **Relative Concept for automation in BIM material quantification and 5'D BIM Coordinated Procurement system**, London, Ontario, Canada, 2016.

CANADIAN/INTERNATIONAL CERTIFICATIONS:

- **Certificate in University Teaching and Learning**, a minor graduate program in Western University Canada with these Components

  (http://www.uwo.ca/tsc/graduate_student_programs/western_certificate/index.html)

  - TA Training/Microteaching Requirement
  - workshops in the Future Professor Series
  - The Teaching Mentor Program for Graduate Students
  - Teaching Portfolio
  - Written project

Completed in Nov.2016

- **Academic and Professional Communication in Canada Certification/** Western University Canada/ Teaching Support Center/ Oct 2016, subprogram certificates:
  - **The Language of Teaching in Engineering/** Western University Canada Teaching Support Center (TSC) /July 2011
  - **Teaching in the Canadian Classroom/**Western University Canada TSC/June 2011
  - **Communication in the Canadian Classroom/**Western University Canada TSC/May 2011

- **The Language of Advanced Discussions/**Western University Canada TSC/June 2011

- **Learn to program the Revit API by Boost Your BIM/** Udemy Dec. 26, 2014
- **Technology Demonstration hands-on training for operation of conventional treatment process/**Walkerton Clean Water Center, An agency of the Government of Canada / August 2011

RELATED GRADUATE COURSES IN CANADA:

- Building Information Modeling (BIM), Western University Canada
- Engineering Planning and Project Management, Western University Canada
- Project Risk Analysis and Management, Western University Canada
- Advanced Project Management, University of Waterloo
- Sensing in Civil Engineering, University of Waterloo
- Computational Wind Engineering, Western University Canada
- Seismic Analysis and Design, Western University Canada
- Advanced Concrete Technology, Western University Canada
- Dynamic (Machine) Foundation Design, Western University Canada
- Water Treatment and Quality Control, Western University Canada
- Offshore Structure Analysis and Design, Western University Canada
- Advanced Mathematical Method in Engineering, Western University Canada

ORGANIZATIONS, INSTITUTES MEMBERSHIP:

- Member of **“Canada BIM Council" (CanBIM)”** - Active committee member in “Technology” and Education Committees: http://www.canbim.com/members
- Member of **"buildingSMART Canada"/**A Council of the Institute for BIM in Canada: www.buildingsmartcanada.ca/members/ (Active committee member in buildingSMART Canada Education Committee) – Working on development of National United Academic BIM curriculum for Canada
- Member of "National Institute of Building Sciences"
- Member of "Canadian Society for Civil Engineering" (CSCE)
- Member of "American Institute of Steel Construction" (AISC)

PROFESSIONAL EXPERINECE

BIM Manager, Coordinator and Researcher/ BIM Technology Developer: (ATCOEM) ATCO Emission Management, Cambridge, Ontario, Canada

Responsibilities as BIM Manager: Developing a BIM construction department, hiring qualified BIM modelers and coordinators, developing BIM workflows for implementation in the whole organization, Selecting BIM software as per defined workflows, developing BIM Execution Plans (BxP) for projects, Checking the BIM models and drawings, developing the complex BIM models and parametric Revit families for projects, Managing the constructability and 3D coordination sessions, developing Primavera/MSP schedules for design/drafting tasks, etc.

Responsibilities as BIM Structural Engineer: Preliminary check of subcontracted structural designs (Pre-Engineered Buildings) according to IBC and Canadian Codes, BIM Structural designer (developing BIM models for structural design, load application, and analysis I,e, Structural Designer for Union Gas Compressor Building)

2013-2015: Projects as BIM Manger/BIM Coordinator, Modeler/Structural Designer

- Acoustical pre-engineered building design, “Lower Colorado River Authority Power Plant,” K033 – “Fluor Enterprises Inc.”, Horseshoe Bay, Texas, USA.
- Acoustical pre-engineered building, powerhouse, Caterpillar project, “Alberta Newsprint Company,” Alberta, Canada.
- Acoustical pre-engineered building design, Compressor Station, “Neuman & Esser USA Inc.”, Riviera Beach, Florida, USA
- Acoustical pre-Engineered building design, Steam Turbine Generator (STG) enclosure, “Garrison Energy Center,” “Kvaerner,” Dover, DE, USA
- Retrofit Acoustical Barriers Pre-Engineered steel structural design, power plant, “Zona Franca Celsia S.A.E.S.”, Barranquilla, Columbia
- Retrofit acoustical barriers and enclosures, “AES Gener,” “Nueva Renca” gas power generation plant, Renca, Chile /”Ventanas” coal power generation plants, Quintero, Valparaíso Region, Chile
- And some other noticeable project such as: Nine acoustical buildings, Dominion Cove Point Power plant Maryland, USA/ STG and HRSG Buildings, Salem Harbor Power Plant, Massachusetts, USA/ TransCanada Pipe-liner, Gas pressure Station #136, Toronto, Canada/ WestJet Calgary Airport, Alstom STG Building, Polk Tampa, FL, USA/ Union Gas Compressor Building, Windsor, Canada
- Developing a new automated quantity take off module for ATCO Building Project.
- Developing new customized 3D families for Revit structure and architecture for ATCO project style.

Ellis Don Corporation, Mississauga, Ontario, Canada

2012 (Sep-Dec): Collaboration in research on "BIM and 3D Laser Scanning with “Ellis Don Corporation” and Western University Canada, London Ontario, Canada.

Project Manager, Coordinator/ BIM Modeler, Designer/ Structural Engineer: Engineering Technical Office #318 – Delavar Engineer Group, Mashhad, Iran

2008-2009: Structural Engineer

- Structural design and shop drawings development, a large-span pyramid shape truss structure, an architectural/monumental element at the top of “Saderat” bank tower (an enormous pyramid shape steel structure with 18m height, 60m length, and 40m width), Mashhad, Iran
- Structural design and shop drawings development, Steel structure/ Two stories, Emergency power supply building, “Saderat” bank project, Mashhad, Iran
- Structural design re-checks (re-analysis for change order from bolted connections to welded connections) for "Maskane Mehr" 1800 Blocks of 4 story buildings with three base layout plan.

2009-2011: Architect, BIM Modeler, Coordinator

- BIM model/design development (architectural 3D model and general arrangement set), "Royal Wedding Palace" with 10000 m2 area of occupancy, Mashhad, Iran
- BIM model/design development (architectural 3D model and general arrangement set), “Farhad building", 5 stories building with 1200 m2 area of occupancy, Mashhad, Iran

2009-2011: Project Manager, Scheduler, Project Coordinator

- Project Scheduler/Coordinator, "Royal Wedding Palace”, Mashhad, Iran
- Project Scheduler/Manager, "Farhad” building, 5 story building, Mashhad, Iran

OTHER WORK EXPERIENCES

"Asar-e-Toos" Construction Corporation, Mashhad, Iran

2009-2011: Project Scheduler, Coordinator

- "Kamal" residential tower – 9 story building with about 33000 m2 area of occupancy
- "Mukhabarat" sport complex

"Mana" Construction Corporation, Mashhad, Iran

2009-2010: Project Scheduler, Coordinator

- "Saderat" bank tower, 17 stories building about 35000 m2 area of occupancy
- Commercial 4 stories building in "Shohada" Square development plan, about 15000 m2

"Pariz-e-Shargh" Construction Corporation, Mashhad, Iran

2009-2011: Project Scheduler, Coordinator

- "Armitage" residential tower, 14 stories building 13000 m2 area of occupancy
- "Sepehr" residential/commercial building, 82 units with 9000 m2 area of occupancy

Construction Software Developer:

- 2010: Designing and developing software for warehouse management in construction Industry
- 2012: Designing and developing software for accounting in construction Industry