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BIM IMPLEMENTATION FOR PRECAST CONCRETE SUPPLY CHAIN MANAGEMENT : CASE STUDY PROJECTS

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A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Civil Engineering

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การสร้างแบบจำลองสารสนเทศอาคาร (Building Information Modeling, BIM) ได้รับการพิสูจน์แล้วว่าเป็นประโยชน์แก่อุตสาหกรรมออกแบบก่อสร้างและการจัดการสิ่งปลูกสร้าง เนื่องจากสามารถช่วยจัดการสารสนเทศงานก่อสร้างอย่างมีประสิทธิภาพประสิทธิผล ในปัจจุบันการสร้างแบบจำลองสารสนเทศอาคาร (BIM) ได้รับความสนใจในวงการอุตสาหกรรมก่อสร้างเป็นอย่างสูงจากความสามารถในการบริหารข้อมูลอย่างมีประสิทธิภาพ แม้ว่าผู้มีส่วนเกี่ยวข้องในงานก่อสร้างทั่วไปสามารถนำ BIM มาใช้ประโยชน์ได้หลากหลาย แต่การประยุกต์ใช้ BIM โดย ผู้ผลิตรับจ้างก่อสร้างชิ้นส่วนคอนกรีตหล่อสำเร็จให้เกิดประโยชน์ยังคงเป็นความท้าทายสำหรับผู้ผลิตชิ้นส่วนคอนกรีตหล่อสำเร็จ เนื่องจากการความซับซ้อนของกระบวนการผลิตและก่อสร้างติดตั้งคอนกรีตหล่อสำเร็จ ความผิดพลาดของการจัดการสารสนเทศอาจนำไปสู่ความผิดพลาด ความล่าช้า และความสูญเสียในงานก่อสร้าง งานวิจัยนี้เสนอกรอบการนำ BIM ไปใช้สำหรับผู้รับจ้างก่อสร้างคอนกรีตหล่อสำเร็จ ซึ่งครอบคลุมถึงกรอบสำหรับประเมินการปรับปรุงห่วงโซ่อุปทานโดย BIM โครงการก่อสร้างบ้านคอนกรีตหล่อสำเร็จ 2 โครงการถูกใช้เป็นกรณีศึกษา ซึ่งผลที่ได้รับจะถูกใช้เพื่อออกแบบกระบวนการนำ BIM ไปใช้ในการก่อสร้างคอนกรีตหล่อสำเร็จ แบบจำลอง BIM ของทั้งสองโครงการได้ถูกพัฒนา และกรอบการประเมิน SCOR ได้ถูกปรับปรุงเพื่อวัดเปรียบเทียบสมรรถนะ (benchmark) ของห่วงโซ่อุปทานบนพื้นฐาน BIM สมรรถนะห่วงโซ่อุปทานของกระบวนการที่ปฏิบัติอยู่และบนพื้นฐานของ BIM ได้ถูกรวบรวม วัดเปรียบเทียบสมรรถนะ วิเคราะห์ และสรุป ผลวิจัยแสดงศักยภาพของ BIM ในการปรับปรุงลักษณะประจำ (attribute) ส่วนมากของห่วงโซ่อุทาน โดยให้ผลลัพธ์ที่ดีกว่าสำหรับการจัดการเอกสาร เวลาสำหรับกระบวนการออกแบบและวางแผนลดลงอย่างมีนัยยะสำคัญ (36.98% และ 41.49%) ในขณะที่ต้นทุนลดลงเล็กน้อย (9.37% และ 17.67%) นอกจากนั้น BIM ยังแสดงศักยภาพในกระบวนการห่วงโซ่อุปทานเร็วขึ้น เพิ่มความแม่นและความยืดหยุ่น กำจัดความซ้ำซ้อน และปรับปรุงความร่วมมือโดยรวม ผลลัพธ์เหล่านี้สามารถนำมาใช้เป็นแนวทางในการนำ BIM ไปใช้ในโครงการคอนกรีตหล่อสำเร็จโดยมีกรอบการประเมินที่เหมาะสม

ภาควิชา วิศวกรรมโยธา	ลายมือชื่อนิสิต ....
สาขาวิชา วิศวกรรมโยธา	ลายมือชื่อ อ.ที่ปรึกษาหลัก ....
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KEYWORDS: BUILDING INFORMATION MODELING / SCOR / SUPPLY CHAIN MANAGEMENT / PRECAST CONCRETE

WONGWISUTH WISUTHSERIWONG: BIM IMPLEMENTATION FOR PRECAST CONCRETE SUPPLY CHAIN MANAGEMENT : CASE STUDY PROJECTS. ADVISOR: ASSOC. PROF. DR. VEERASAK LIKHITRUANGSILP, CO-ADVISOR: ASSOC. PROF. DR. PHOONSAK PHEINSUSOM, 150 pp.

Building Information Modeling (BIM) has been proven beneficial for the AEC/FM industry because it assists in managing construction information efficiently and effectively. Even though all construction stakeholders can gain benefits from BIM, it is challenging for precast concrete contractors to implement and exploit benefits from BIM. Due to the complexity of precast concrete manufacturing and construction processes, the deficiencies of precast concrete information management contribute to construction work errors, delays, and losses. This research proposes a BIM implementation framework designed specifically for precast concrete contractors. It also encompasses a framework for assessing supply chain improvements by BIM. Three precast concrete housing projects are investigated as case studies, the results of which are used to determine BIM implementation processes for precast concrete contractors. BIM models of two projects are developed, and the Supply Chain Operations Reference (SCOR) assessment framework is modified to benchmark BIM-based supply chain performances. The outcomes are compared and analyzed. The supply chain performances of conventional and BIM-based processes are collected, benchmarked, analyzed, and concluded. The results shows BIM potentials to improve most supply chain attributes with better outcomes for documentation. For design and planning processes, times are reduced significantly at 36.98% and 41.49%, while costs are reduced slightly at 9.37% and 17.67%. BIM also shows potential to accelerate supply chain processes, increase accuracy and flexibility, eliminate working redundancies, and improve overall collaboration. These findings can be used as a guideline to implement BIM for precast concrete contractors with a proper assessment framework. It also improves overall knowledge of supply chain management for the precast concrete industry.

Department:	Civil Engineering	Student's Signature	....
Field of Study:	Civil Engineering	Advisor's Signature	....
Academic Year:	2014	Co-Advisor's Signature	....

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CHAPTER I
INTRODUCTION

1.1 Motivation

Precast concrete has been used in Thailand for decades. It entails manufacturing concrete products under factory conditions and assembling them on a construction site. Compared to the conventional method, precast concrete provides significant advantages for construction success factors (e.g., time, cost, and quality). Regarding construction time, precast concrete products can be manufactured in advance and transported to the project site at the required time, leading to a decrease in construction duration. Construction unit costs can be minimized while improving the quality, because the products are normally manufactured in large quantities under controlled factory condition. Furthermore, various factors are substantially accelerating the growth of the precast concrete industry, such as labor shortage, safety issues, increase in minimum wage, and limited space in construction sites. Undoubtedly, precast concrete plays a pivotal role in the current construction industry.

To date, there are various management theories for precast concrete management, such as Supply Chain Management (SCM), Just In Time (JIT) Management, Lean Supply Chain Management (Lean SCM), and Enterprise Resource Planning (ERP). Among these theories, SCM is one of the most popular management concepts, which was introduced in the 1990s. SCM has proven beneficial for minimizing inventory, lead time reduction, waste removal, and improving long term relationships between companies (Lehtinen, 2010). However, precast concrete management is still undervalued in SCM owning to significant losses in the construction supply chain, causing an unavoidable reduction of its productivity (Nummelin et al., 2011 ; Limsupreeyarat, 2005). Moreover, as compared to SCM for other manufacturing industries, the SCM for precast concrete contractors is imperfect and considerably varies in different projects. This is because precast concrete generally encompasses a discrete manufacturing process, rather than a repetitive one. As a result, a specific project-based system is required to solve such deficiencies of SCM for precast concrete management.

The emergence of IT has had a great impact on the construction industry. At present, IT in construction has reached the third era, in which the technology itself does not only focus on an individual application, but also integrate through the whole systems of the operation (Froese, 2010). The advancement of IT has led to overall change in SCM (Gilaninia et al., 2011). One of the technologies that can address the problems concerning construction information is called Building Information Modeling (BIM). BIM is considered as a tool for generating and managing information of the building (Sack et al., 2005). BIM has proven beneficial for the AEC/FM industry because it assists in managing construction information effectively and efficiently. The construction industry is definitely moving forward with BIM (Hergunsel, 2011).

BIM has been utilized in the precast concrete industry for several years. There were many research projects investigating BIM implementation on precast concrete contractors, most of which focused on the technical aspects. Precast concrete contractors begin to realize the benefits of BIM on an enterprise level (ManuBIMsoft, 2012). Furthermore, the Information Delivery Manual (IDM) for precast concrete was developed as a guideline for precast concrete contractors, which was a part of the National Building Information Modeling (NBIM) standard (LaNier et al., 2009). It led to the development of BIM for precast concrete contractors and other fabricators.

1.2 Problem Statements

Typically, precast concrete construction processes consist of design, planning, production, transportation, and erection. The processes usually encounter various difficulties concerning information management such as the complexity in design and construction, dynamic information, large quantity of paper-based documents, numerous participants, time constraints, changes, and limited resources. Although BIM can serve as a tool for managing construction information efficiently, the applications of BIM are still challenging for most precast concrete contractors. There have also been a limited number of research projects that address BIM in the supply chain of precast concrete contractors. Furthermore, the knowledge about BIM applications for precast concrete contractors is also scarce (Hamilton, 2012).

The critical questions that need to be addressed are as follows.

- How to implement BIM for precast concrete contractors?
- How to develop a suitable BIM model for production and construction tasks?
- How to assess improvements in a precast concrete supply chain resulting from BIM implementation?
- What are major concerns for precast concrete BIM adoption?

1.3 Research Objectives

The objectives of this research are:

i) To determine BIM implementation processes for precast concrete contractors.

ii) To determine an appropriate way to develop a precast concrete BIM model.

iii) To develop suitable assessment metrics for precast concrete supply chain management.

iv) To determine supply chain improvements resulting from BIM implementation.

1.4 Scope of Research

The research was conducted to investigate precast concrete supply chain improvements resulting from BIM implementation by considering the information from project acquisition to project completion. A bidding process was not included in this research. The processes of source and return in a supply chain were excluded as they are not major concerns for BIM implementation. Two precast concrete housing projects of a single case study company were selected as case study projects. The implementation was also based on available BIM tools to avoid the copyright infringement issues. The research was based on precast concrete practices in Thailand with the limited duration of one year.

1.5 Research Steps

Figure 1.1 illustrates the procedure of this research, which was divided into nine main steps.

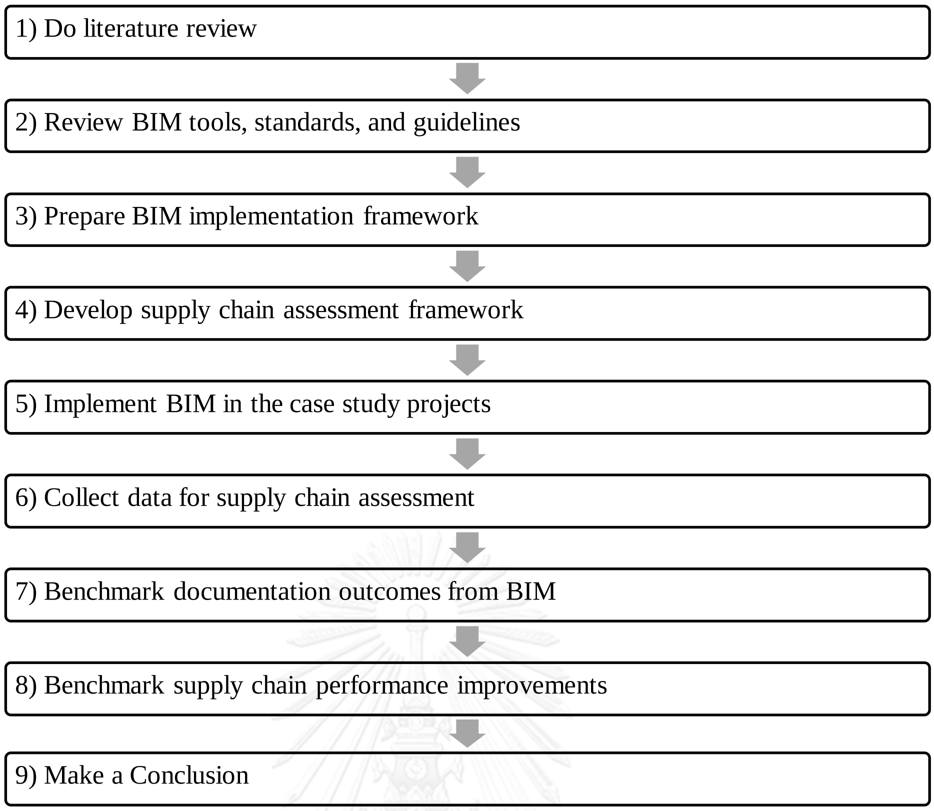

Figure 1.1: Research steps

CHAPTER II
LITERATURE REVIEW

The results from the literature review is presented in this chapter. It consists of three sections: precast concrete contractor (section 2.1), building information modeling (section 2.2), and supply chain management (section 2.3).

2.1 Precast Concrete Contractor

2.1.1 General

Precast concrete is one of the most popular fabrication techniques in the construction. Although precast concrete system was pioneered since 1900s, it gained popularity in the post-world war II era due to high requirements of shelter. For Thailand, precast concrete system has been introduced for decades. Besides benefits to construction key success factors (e.g., time, cost, quality, and safety), there are several factors that accelerate the growth of a precast concrete industry, such as labor shortage, safety issues, limited space in the construction project, and quality control issues.

From the definition, the term precast concrete can be referred to as any concrete product manufactured under factory conditions, transported to a construction site, and assembled as a part of a structure. In this research project, the term precast concrete contractor is used to refer to a party who is responsible to design, manufacture, transport, and erect precast concrete products to form a structure.

Precast concrete products can be classified based on the structural behavior into two main types: structural precast concrete and architectural precast concrete. Also, the product can be classified based on the production technique into two main types: reinforced precast concrete and pre-stressed precast concrete.

Based on the product distribution, Sittimongkolchai (2008) explained the classification of precast concrete factory, which can be divided into three types: permanent factory, semi-permanent factory, and temporary factory. Figure 2.1 illustrates the different distribution types of precast concrete factory.

i) Temporary factory

Temporary factory locates inside a specific construction site and supplies products only for that project. The factory is removed after the production is completed.

ii) Semi-permanent factory

Semi-permanent factory locates in a construction site, manufactures the products for that project and nearby projects. The factory is also removed after the production is completed.

iii) Permanent factory

Permanent factory locates permanently on a specific area and distributes products to nearby projects.

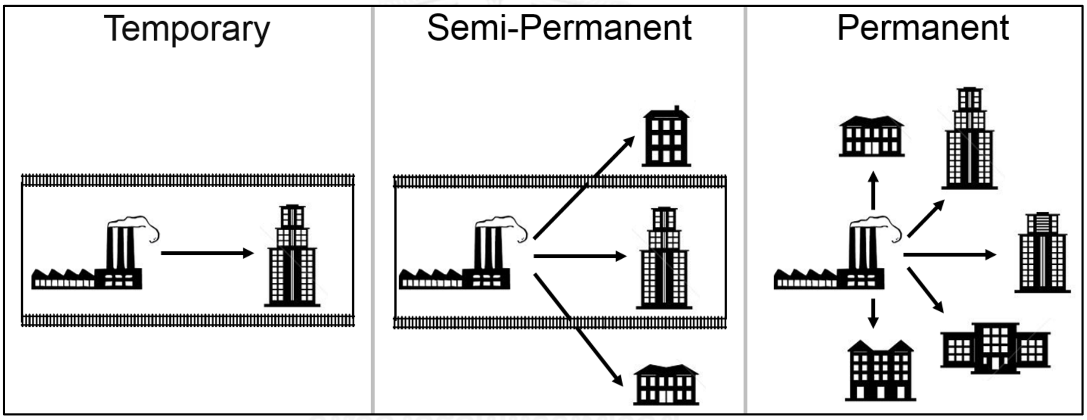

Figure 2.1: Types of precast concrete factory

From the classification, it is obvious that the permanent precast concrete factory has the largest scale of production, largest product distribution, and most potential for BIM adoption.

2.1.2 Manufacturing process

Though a manufacturing process of precast concrete can vary from the difference in equipment, working technique, product design, labor skill, etc., there are similarities in the process. In general, a precast concrete production process can be separated into nine steps: mold assembly, oil spraying, reinforcement placement, embedded part placement, concrete casting, concrete vibrating, curing, mold stripping, and product finishing.

i) Mold assembly

Mold assembly is the first step for precast concrete production. After the product design receives an approval, concrete molds are assembled based on the design. Mold assembly is generally performed by using manpower.

ii) Oil spraying or oil painting

Oil must be sprayed or painted thoroughly on the internal surface of a steel mold to prepare for a mold removal process.

iii) Reinforcement placement

After the mold is properly assembled and oil-sprayed, the reinforcements is placed according to the design. The placing process requires a sequence, for example, stirrups must be placed before steel bars.

iv) Embedded part placement

Similar to reinforcement steel bar, an embedded part is placed in the mold according to the product design. The embedded part is usually attached to the reinforcement to fix it in the required position.

v) Concrete casting

Concrete casting follows the placement of reinforcement steel bar and embedded part. As concrete casting process is irreversible, concrete molds, reinforcement bars, and embedded parts must receive an approval from the quality control unit before casting. After casting, the concrete surface must be smoothened using manpower or a machine.

vi) Concrete vibrating

The concrete must be vibrated to fill the mold properly during the casting process.

vii) Mold stripping

After concrete is settled, the mold is removed, cleaned, and prepared for future usages.

viii) Curing

Curing process follows a concrete casting process to accelerate the strength development. The curing method can be performed using various techniques, such as wet covering, water spraying, stream curing, etc. The curing process is generally performed before and after a mold stripping process.

ix) Product finishing

Product finishing process is used to treat defections on concrete products (e.g., uneven surface, and crack). After a final approval, the product is moved to a stockyard area and prepared for the delivery (Ko, 2010 cited in Ko, 2012).

2.1.3 Benefits and drawbacks

Precast concrete provides benefits to the key success factors of construction projects as follows.

i) Time

Precast concrete products can be manufactured in advance and deliver to a project site on the required time, while the conventional method must follows a construction sequence. It has been proven that a precast concrete system can reduce an overall project duration significantly.

ii) Cost

The manufacturing process has an advantage on mass production, as an equipment can be reused to improve cost efficiency. The manufacturing process also substitutes manpower with a machine or equipment. It results in a great reduction of a labor cost.

iii) Quality

For precast concrete products, a quality control process can be performed with ease under the factory environment. Material wastages and space requirements on a construction site can be minimized. The productivity of a construction is stabilized by using a machine instead of manpower. Furthermore, a manufacturing process is independent from an adverse weather condition (Rathnapala, 2009).

iv) Safety

Construction safety can be improved when works are performed under factory conditions. The quality control process can be performed with ease. Risks of accident from adverse environmental conditions, such as height, fire, and falling objects, can be directly eliminated.

Though precast concrete provides various benefits for construction projects, there are some drawbacks from the system. Precast concrete requires a proper design from the very beginning of a project. As the manufacturing process is irreversible, an insufficient duration for design processes becomes problematic issues. Changes can not be performed with ease. A construction project requires a good cash flow to use a precast concrete system, as a precast contract is generally in a form of a purchase order. Precast concrete also requires a good management system to coordinate between production and erection processes. Without effective collaboration between precast concrete contractor and main contractor, a project is fallible for delay and mistakes.

2.1.4 Precast concrete contractor and BIM

Eastman et al. (2008) described four ways of impacts from BIM to the construction prefabricators. First, an implementation of BIM can directly reduce most errors in the design phase. With an accurate design, a product life cycle time can be shortened. This error reduction also increases the production capability. Second, BIM provides an ability to corporate time parameter with a model. The scheduling process can be simplified with greater workflow stability. Third, an implementation of BIM collaborates stakeholders in a project. Theoretically, buffer times in construction can be reduced from an improvement in collaboration. And forth, BIM accelerates a shop drawing production. Prefabricators can gain various benefits from the reduction of an inventory.

Hergunsel (2011) explained that a manufacturing process requires high accuracy for both design and operational tasks. With BIM, a user can achieve this level of accuracy by including specifications, sequences, finishes, and three-dimensional visualization to the components in a BIM model.

Gerber and Rice (2010) investigated usages of BIM in United Kingdom (UK) construction industry. Figure 2.2 illustrates BIM applications of the survey participants in UK. From the survey results, the usage of BIM for direct fabrication was comparatively low at 23.20%. Rathnapala (2009) supported the statement that BIM interaction between contractor and prefabricator was highly ambiguous.

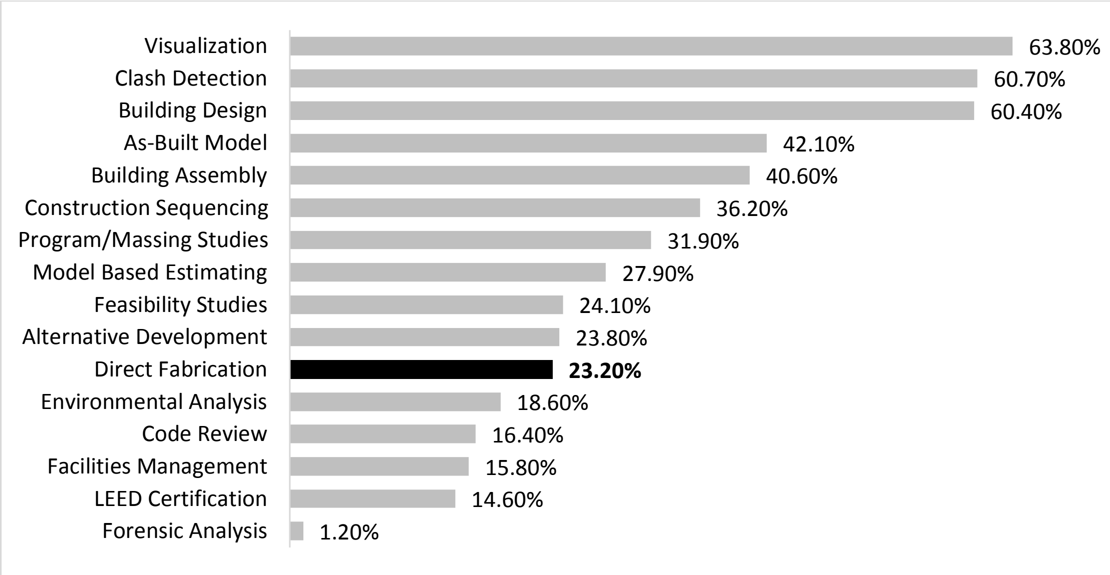

Figure 2.2: BIM applications in UK construction (Gerber and Rice, 2010)

ManuBIMsoft (2012) explained the contributions of BIM towards a manufacturing industry. In general, at the beginning of a project, the design is un-finalized and has high tendency to change. These imprecise information always causes problematic issues to designers. Using a BIM model, an accurate information can be obtained at the very beginning of a project, which improves project planning, reduces overall risks, and greatly enhances working flexibility.

Sack et al. (2005) investigated BIM implementation on precast concrete engineering firms. The authors explained that BIM can reduce lead times between engineering design and precast concrete production because both processes can collaborated properly through BIM applications.

BIM can integrate construction stakeholders and enhance a supply chain system. The supply chain improvement leads to improvements in material scheduling, increased work efficiency, and reduced the wastage in management (Smith, 2012). Hamilton (2012) supported the statements that a supply chain integration is one achievable benefit from BIM adoption. Among prefabricators, steel suppliers can utilize BIM to an advance level, while precast concrete contractors still requires a great development.

Eastman et al. (2008) categorized prefabricate products into three types: made-to-stock, made-to-order, and engineered-to-order components. This product classification is similar to the classification of a supply chain standard. However, it was proposed based on the degree of an engineering design.

i) Made-to-stock component

Made-to-stock component is a basic type of product with a fixed standard for usage. The product is manufactured without a customer order, stored in a stockyard, and distributed on a purchase. The examples of made-to-stock products are precast concrete slab, precast concrete pipe, etc.

ii) Made-to-order component

Made-to-order component has a fixed production standard but requires partial specifications from a purchase order. The examples of made-to-order component are pre-stressed concrete pile, pre-stressed concrete girder, etc. The pile has a fixed standard (e.g., cross sectional area, concrete strength, etc.), but still requires some specifications (e.g., pile length, etc.) for production.

iii) Engineered-to-order component

Engineered-to-order component is unique, as it must be designed accordingly to a specific order. The examples of engineered-to-order component are the members of steel frame, precast concrete wall panels, etc. The products require great information management with high flexibility. BIM can maximize benefits for this type of a precast concrete component.

Rathnapala (2009) studied BIM applications for prefabrication processes. The author stated that BIM can provide benefits in design and manufacturing processes for prefabricators. Although these benefits were realized, the implementation of BIM would not be a revolution to a precast concrete industry.

Venugopal et al. (2012) explained problems of the traditional information exchanges between designer and precast concrete contractor. In general, the design does not transfer directly from a designer to precast concrete contractor. It must be transferred from a designer to general contractor, and from general contractor to precast concrete contractor. After precast concrete contractor develop product drawings, they must be transferred back in the same way for validation. These indirect collaboration causes delays and reworks. This problem could be minimized by improving the interoperability between BIM tools and other applications.

Eastman et al. (2012) explored interoperability issues in a precast concrete engineering. The authors classified a precast concrete engineering into four processes: architectural design, structural design, product detailing, and management. The data exchange from preliminary design to management was divided into six parts as follows.

i)	Exchange One	: from architectural design to structural model
ii)	Exchange Two	: from structural design to architectural model
iii)	Exchange Three and Four	: from design model to precast detailing system
iv)	Exchange Five and Six	: from detailed design to management

Figure 2.3: A simplified workflow of precast model exchanges (Eastman et al., 2012)

From Figure 2.3, the workflow starts from an architectural design. When an architectural design is completed, it is transferred to an engineering unit for a structural design. An engineering unit must create structural drawings, and transfers them back for validation. Then, precast production drawings can be developed in a detailing process. BIM tools are utilized from an architectural design to product detailing process. Finally, the detailed production models are transferred to a management process for quantification, scheduling, etc. It is obvious that a standard for data exchange is required to corporate between different applications and working units.

Kaner et al. (2008) studied BIM adoption for engineering firms. The research focused on a precast concrete design with four objectives: to increase design flexibility, to improve productivity, to eliminate errors, and to visualize structure in three dimensions. The author stated that BIM can improve productivity considerably in modeling and drawing processes, but BIM ability for a structural analysis could not be achieved in a short duration. The authors also proposed the SWOT analysis for implementing BIM in precast concrete engineering companies. Table 2.1 demonstrates the SWOT analysis of BIM adoption for precast concrete engineering firms.

Table 2.1: SWOT analysis of BIM adoption for precast concrete engineering firms (Kaner et al., 2008)

Strengths	Weaknesses
Skilled engineering staff experienced in CAD and other software	Skilled BIM modelers are in short supply and are costly to train
Appropriate IT infrastructure helps access to advance software	Adoption requires capital investment
BIM provides leadership with vision	
Opportunities	**Threats**
Increase engineering productivity	Varying workloads
Enhance competitiveness of engineering services through reduced design lead times and virtual elimination of geometry and design consistency errors	Dependence on a small number of engineers with BIM expertise
Provision of new services for owners and contractors	Staff that are unable or unwilling to adapt may feel threatened
	Drawings can not be produced with absolute automation. Manual process is still required
	Inability to remain profitable without BIM if the competitors also adopt BIM

Sack et al. (2005) conducted a research on BIM adoption to find its impacts on precast concrete engineering firms. The improvements of BIM adoption were investigated by benchmarking direct benefits, indirect benefits, and costs. Table 2.2 lists the factors concerning benefits and costs for three-dimensional modeling. Overall, the benchmarked results showed significant improvements in an annual basis.

Table 2.2: Benefits and costs of adopting 3D modeling in precast engineering (Sack et al., 2005)

No.	Benefits	Costs
1	Improved project definition at time of sales	Direct costs of 3D BIM stations
2	Enhanced cost estimating accuracy	Replacement costs of existing systems
3	Reduced cost of engineering	Indirect costs through adoption phase
4	Reduction of design and drafting errors	
5	Improved customer service	
6	Streamlined logistic	
7	Production automation	
8	Reduced overhead cost rate	

Table 2.3: Benefits and costs assessed by a large precast company (Sack et al., 2005)

Activity	Year 1	Year 2	Year 3	Year 4
Annual predicted cost of sales	$40,000,000	$42,000,000	$44,100,000	$46,305,000
Direct benefits				
Engineering productivity	$216,000	$680,400	$952,560	$1,000,188
Error reduction	$45,000	$141,750	$198,450	$208,373
Costs				
Equivalent CAD work stations required	18	19	20	21
CAD stations saved	0	4	9	20
3D modeling work stations	3	6	12	13
Added work station costs	$45,000	$45,000	$90,000	$15,000
Indirect 3D costs	$30,000	$31,500	$33,100	$34,800
Net benefits				
Net annual direct benefit	$186,000	$745,650	$1,027,910	$1,158,761
Indirect benefit				
Potential annual volume/overhead gain	$0	$247,291	$532,294	$859,492

Sack et al. (2002) classified design errors in precast concrete engineering into five types as follows.

i) Design and engineering errors.

ii) Errors from inconsistencies between assembly drawings and production drawings.

iii) Errors from lack of coordination between different systems.

iv) Errors from changes.

v) Other types of errors, such as errors in Bill of Quantity (BOQ).

The authors stated that these errors can be eliminated by using parametric three-dimensional computer modeling tools.

2.2 Building Information Modeling (BIM)

2.2.1 Definitions

On the second era of Information Technology (IT), flows of construction information has been performed and managed by using two-dimensional drawings and paper-based documents. It has been proven that this conservative method hindered overall performances in a construction industry (Johansson and Jonasson, 2011). This practice led to difficulties in computing data, insufficiency of information, errors from manual processes, and delay. After IT have reached the third era, the technology starts moving forward to integrate systems as a whole (Froese, 2010). Building Information Modeling (BIM) concept has been emerged to solve these problems concerning information in the AEC/FM industry (GSA, 2007 cited in Lehtinen, 2010). From the different perspectives, there are various definitions for BIM. Some of the definitions are described as follows.

BIM is “a digital representation of physical and functional characteristics of a facility and a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition” (National Institute of Building Sciences, 2010: online cited in Hergunsel, 2011).

Eastman et al. (2008) stated that “BIM integrates all of the geometric model information, the functional requirements and capabilities, and piece behavior information into a single interrelated description of a building project over its life cycle. It also includes process information dealing with construction schedules and fabrication processes”

Autodesk, the BIM tool developer stated that “Building Information Modeling (BIM) is an intelligent model-based process that provides insight for creating and managing building and infrastructure projects faster, more economically, and with less environmental impact” (Autodesk ,2011: Online cited in Roginski, 2011).

BIM is “A computable representation of the physical and functional characteristics of a facility and its related project / lifecycle information using open industry standards to inform decision making for realizing better value” (NBIMS, 2007 cited in Kaner et al., 2008).

Overall, BIM is a comprehensive concept that can be defined in different perspectives. It can be used to refer to as a product, a system, or an activity (NIBS, 2007 cited in Lehtinen, 2010). Figure 2.4 illustrates the conceptual image of BIM through different phase of a construction project.

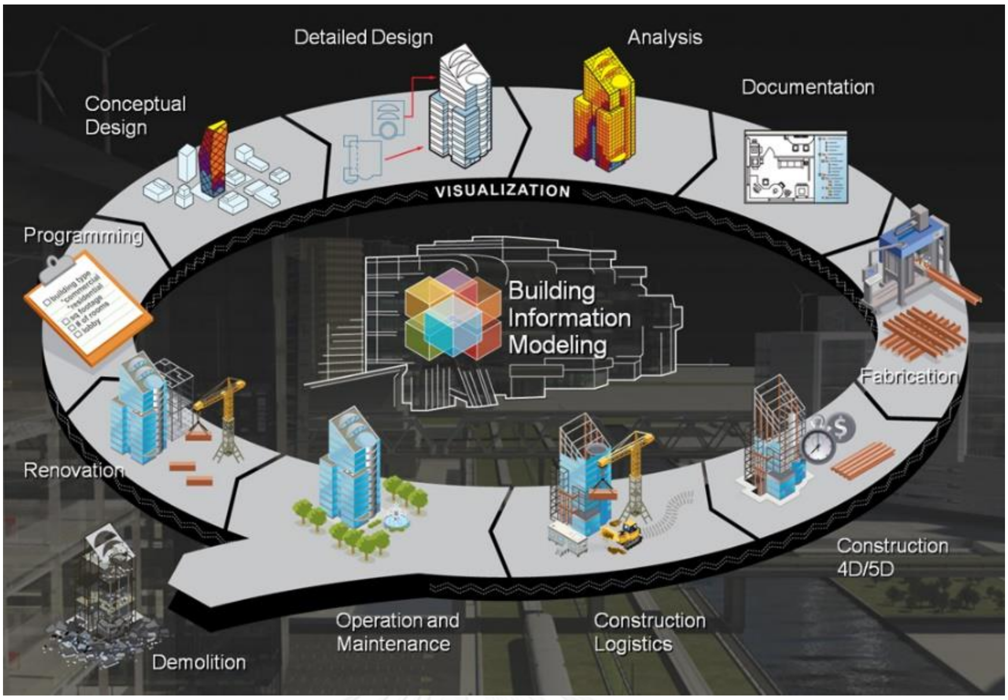

Figure 2.4: BIM illustration (Dispensa, 2010 : Online)

2.2.2 Implementation

Krantz (2012) divided BIM implementation into three levels: visualization, integration, and automation. First, visualization is the benefit of using a three-dimensional model to improve understandings of a design between project stakeholders. Second, integration is an ability to integrate a BIM model to other applications, for example, a scheduling application can be integrated with a BIM model for project scheduling and monitoring. And third, automation is to apply advance techniques and tools to corporate with a BIM model, such as RFID tags, high definition camera, and steel bending machine.

Sukki (2011) surveyed factors concerning BIM usages in Thailand. The interviews were conducted between different project stakeholders to determine key factors for a BIM adoption. Figure 2.5 illustrates BIM applications between construction and design firms.

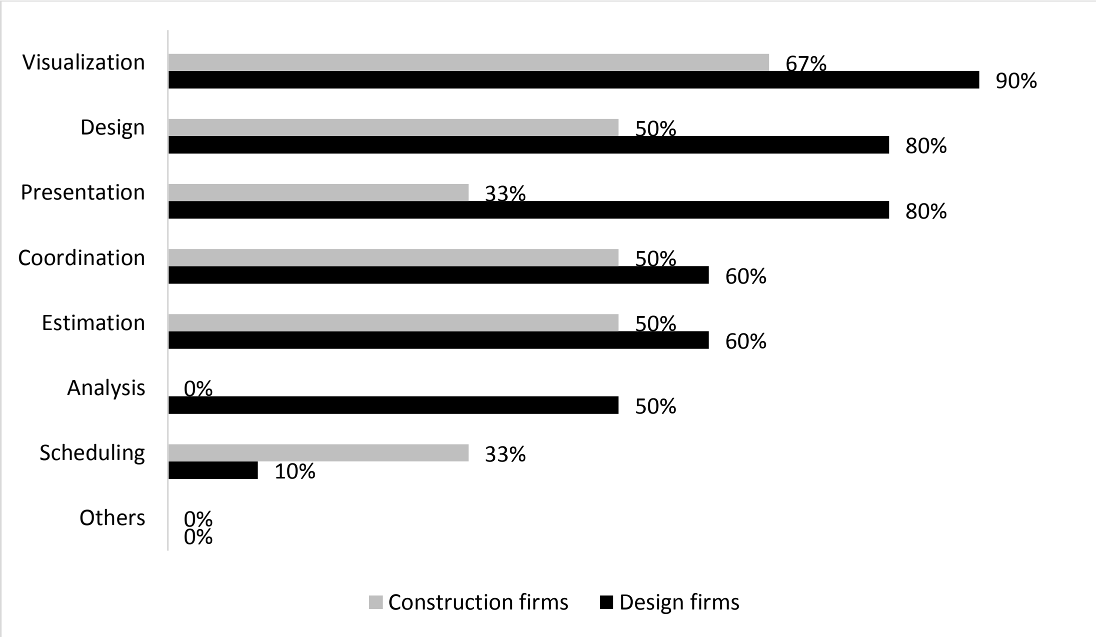

Figure 2.5: BIM applications between construction and design firms (Sukki, 2011)

From the results, the most expected benefits from BIM implementation were visualization, three-dimensional model creation, shop drawing production, quantification, and collaboration respectively. However, the benefit for offsite fabrication might still be insignificant in the year this research was conducted.

A framework is another important basis for BIM implementation. Jung and Joo (2011) developed a framework to identify BIM driving factors. The proposed framework was categorized into three dimensions: BIM technology, BIM perspective, and Construction Business Function (CBF). The authors concluded that the knowledge and reasoning are the keys to advancements in BIM.

Mom and Hsieh (2012) proposed a performance assessment framework for BIM implementation. The proposed framework was separated into four parts: BIM perception model, BIM adoption model, BIM performance model, and BIM capability maturity model. First, a perception model is used for evaluating the benefit, cost, and risk for BIM adoption. Examples of perception model are the Return On Investment (ROI) technique. Second, an adoption model is used to define Critical Success Factors (CSFs) of a project. An example of adoption model is the SWOT analysis. Third, a performance model is used to derive Key Performance Indicators (KPIs) for measuring implementation performances. And forth, a BIM capability model deals with an interaction between BIM capability and BIM maturity. The authors concluded that the proposed framework can accelerate a BIM adoption process and ensure competitive advantage for an organization.

BIM has been proven beneficial in the construction industry. Some benefits from BIM are described as follows.

- Visualization

  Visualization is the first benefit of BIM. It can be referred to as an ability for all stakeholders to visualize and clarify a model of a construction project. It provides a better method of communication and illustrates the design in three dimensions (Hamilton, 2012).

- 3D Coordination / Interference detection

  3D coordination is a three-dimensional interference detection ability of BIM. It helps project stakeholders to collaborate their designs and determine errors (Hergunsel, 2011). For example, a structural model and MEP model can be combined to determine interferences between them.

- Cost estimation / Quantification

  By implementing BIM, a quantity takeoff process can be performed automatically with higher accuracy, lower cost, and shorter duration. The risk of errors for a preliminary estimation can be directly eliminated (Sack et al., 2005). The flexibility of a quantification process can be improved significantly using BIM, especially for changes. It also can improves overall performance for a construction bidding process.

- Record model

  Using BIM, information can be collected and updated systematically throughout the construction phase. An as-built model is gradually generated from the additional information along processes in construction. When the project is completed, an as-built model can be obtained as the final outcome from BIM. This benefit can directly eliminate the redundant tasks of as-built model creation for general contractors.

- Planning and monitoring

  BIM technology provides an ability to connect a model with scheduling applications. Therefore, scheduling and monitoring processes can be performed accurately with ease.

- Analysis

  BIM provides an ability to corporate a model with analysis applications, such as structural analysis software, MEP analysis software, etc. It can improves the collaboration between different working units.

- Facility management

  Using BIM, information generated during a construction phase can be utilized for Facility Management (FM). The building information can be centralized and used to enhanced overall facility management of the building. However, the direct usage of BIM for facility management is still unpopular in this industry.

- Supply chain integration

  The integration between BIM and a construction supply chain is considered as an advance practice for BIM implementation. Using BIM technology, information can be integrated through a supply chain to manage and improve construction logistic for timely delivery (Hamilton, 2012).

Barlish (2011) proposed a new methodology to assess benefits of BIM adoption. The proposed assessment methodology were divided into three sections: return metrics, investment metrics, and organizational considerations. The return metrics and investment metrics were prepared for tangible outcome assessments. The return metrics consist of Requests for Information (RFI), change orders, and duration improvement, while the investment metrics consist of cost assessments for design and construction. The organizational considerations deals with intangible outcomes, such as communication, risk management, change management, etc.

Johansson and Jonasson (2011) studied BIM applications to improve the reinforcement process for four construction stakeholders: client, designer, supplier, and contractor. The authors stated that BIM usages were limited due to lacks of knowledge and expertise. To implementation BIM, the human aspects, such as attitude, and relationship, should be considered as well as technical aspects. From the results, BIM showed great potentials to improve an overall reinforcement process. In addition, the authors suggested that the collaboration between construction stakeholders is a vital key for an advancement in BIM.

Hergunsel (2011) conducted a research on a BIM-based scheduling. The results showed that a BIM-based scheduling has high potentials to improve quality control, quality assurance, and punch list completion.

Roginski (2011) researched BIM applications for a bidding process. From the interviews, the results showed that mistakes in a bidding process were mainly caused from two factors: insufficient duration before the tender, and lack of sufficient information. These mistakes resulted in an unreliable estimation and financial risk. According to BIM workflows, an accurate information can be included in bidding documents through a BIM model. The bidding process can gain direct benefits by implementing BIM from the very beginning of a construction project.

Kuehmeier (2008) researched impacts of BIM to design and construction firms. The interviews were conducted on construction management and design companies. From the results, the key benefits of BIM were fast and accurate cost estimation, contract sum reduction, and elimination of unbudgeted changes. The author stated that BIM can increase company productivity significantly from the reduction of redundant activities.

Although BIM was proven beneficial, BIM utilization was also troublesome. Arayici et al. (2011) stated that BIM requires significant changes at almost every level in a building process. Because trainings and workflow reinvention were required, the management should pay attention to people and process as much as a BIM technology. The authors suggested that BIM implementation should be performed in a bottom-up approach to reduce human resistance and increase controllability. In addition, the authors stated that top management is the most important critical success factor for BIM implementation.

Both and Kindsvater (2012) argued that BIM benefits may be exaggerated by software vendors. The survey was conducted to determine BIM potentials and barriers for implementation. Unfortunately, the selected case studies were fast-track projects, which BIM could not be properly implemented. Kuehmeier (2008) supported the statement that BIM is unable to provide significant advancements in productivity for a fast-track project. Overall, the major barriers were related to four issues: technological, general, normative, and education. Barlish (2011) stated that positive outcomes from some literatures are incorrect as measurement metrics were inconsistent.

Interoperability is another problematic issue for BIM implementation. It can be defined as the "dynamic exchange of information among all applications and platforms serving the entire building community throughout the life cycle of facilities" (Keller, 2004 cited in Kuehmeier, 2008). The interoperability problems are generally occurred between different software applications, such as structural analysis software. Burt (2009) suggested three ways to achieve a BIM interoperability problem. First, by using the software that read similar file format, which are usually provided by the same software developer. Second, theoretically, by using a software that incorporates with developed interface between different providers. This interface is known as Application Programming Interface (API). And third, by using the software that supports industry accepted data exchange standards. The Industry Foundation Classes (IFC) is a good example of the successful data exchange standard for BIM interoperability.

Rohena (2011) stated that costs of software and hardware upgrades are other top BIM obstacles. As BIM tools require high performance equipment, the cost of hardware rises accordingly. Sack et al. (2005) added costs of staff training and productivity loss during an adoption phase as direct costs of BIM implementation.

Smith (2012) explained problematic issues of copyright and patent. As the information shared in a BIM model contains technical knowledge or confidential information of a company, a sharing process would result in losses of a competitive advantage of a company. The author suggested Intellectual Property Rights (IPR) license as a solution.

Krantz (2012) investigated driving forces and resistors for BIM implementation in a production phase. Table 2.4 lists the summary of driving forces and resistors of BIM implementation.

Table 2.4: Summarized driving forces and resistors of BIM (Krantz, 2012)

Driving forces	Resistors
Enhances collaboration and communication	Negative attitudes
Visualization of project and scope	Uncertainty of the legal ownership
Accuracy of coordination	Uncertainty of responsibility over accuracy
Effective work	Hard to measure profitability
Less errors	Expensive implementation cost
Shorter production phase	Expensive design phase
Predictable life cycle cost	
Lower total cost	

2.2.3 Standards

There are various standards developed for BIM users, such as National BIM standard, Singapore BIM Guide, UK BIM Standard, etc. These standards include classifications, guidelines, specifications, and practices of BIM for every phase of the construction. National standard of Building Information Modeling (NBIM) is one of the most accepted standards in a national level, which has been developed by the committee of the National Institute of Building Science (NIBS). It can be defined as "a set of interoperable standards for exchange of building and infrastructure data through the life-cycle of a project" (LaNier et al., 2009). By adopting NBIM, an enterprise can gain benefits from error reduction, increase in work efficiency, improvement in collaboration, redundancy reduction, etc. Furthermore, NBIM focuses on interoperability issues between different BIM software (Harris, 2007). The development resulted in an Industry Foundation Class (IFC), which BIM users can obtain benefits from an integration between different BIM software.

Information Delivery Manual (IDM) for precast concrete is developed as a subset of an IFC model and NBIM standard. It is used to clarify information items in each process and identify relationships between the information exchange models for precast concrete contractors. Based on the variety of precast concrete contracts, Panushev et al. (2010) classified information flows of precast concrete into three types: architectural, precast concrete contractor as prime contractor, and precast concrete contractor as subcontractor. A concrete member which does not subject to structural loads is considered as an architectural precast concrete, such as a concrete façade wall panel, etc. Precast concrete as a prime contractor leads a construction project, while precast concrete as subcontractor follows directions from a general contractor. With these differences in a contractual relationship, the information flow models vary for different precast concrete contractors.

Furthermore, from IDM, information Exchange Models (EMs) are used to define processes for information flow in a generic chart. An exchange model can be presented in text descriptions, detailed specifications, or displayed the relationships as a whole. These generic information exchange models were properly explained in details in the IDM. To apply IDM practically, a new process can be defined, connected with selected activities from IDM, and adjusted accordingly to fit characteristics of an organization (LaNier et al., 2009).

2.3 Supply Chain Management

2.3.1 Definitions

Since 1990s, Supply Chain Management (SCM) has been introduced and gain popularity rapidly in a manufacturing industry. From different perspectives, there are numerous definitions for supply chain management, some of them are described as follows.

Supply chain management can be defined as “The network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services in the hands of the ultimate customer” (Christopher, 1992 cited in Vrijhoef and Koskela, 1999).

“A supply chain is defined as a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer” (Mentzer et al., 2001 cited in Perry II, 2012).

“The supply chain refers to all those activities associated with the transformation and flow of goods and services, including their attendant information flows, from the sources of raw materials to end users" (Ballou, 2004 cited in Petterson, 2012).

Table 2.5 distinguishes the characteristic differences between traditional management and supply chain management.

Table 2.5: Characteristic differences between tradition management and supply chain management (Cooper and Ellram, 1993 cited in Vrijhoef and Koskela, 1999)

Element	Traditional management	Supply chain management
Inventory management approach	Independent efforts	Joint reduction of channel inventories
Total cost approach	Minimize firm costs	Channel wide cost efficiencies
Time horizon	Short term	Long term
Amount of information sharing and monitoring	Limited to needs of current transaction	As required for planning and monitoring processes
Amount of coordination of multiple levels in the channel	Single contract for the transaction between channel pairs	Multiple contacts between levels in firms and levels of channel
Joint planning	Transaction based0	Ongoing
Compatibility of corporate philosophies	Not relevant	Compatibility at least for key relationships
Breadth of supplier base	Large to increase competition and spread risks	Small to increase coordination
Channel leadership	Not needed	Needed for coordination focus
Amount of sharing risks and rewards	Each on its own	Risks and rewards shared over the long term
Speed of operations, information and inventory level	Warehouse orientation (storage, safety stock) interrupted by barriers to flows; localized to channel pairs	Distribution center orientation (inventory velocity) interconnecting flows; JIT, quick response across the channel

2.3.2 Frameworks

Since 1996, the Supply Chain Council (SCC) developed a standard to manage and improve supply chain system called the Supply Chain Operations Reference (SCOR) model. The model standardized a framework to integrate processes, people, working technique, performance assessment method, and technology together. By implementing SCOR, an organization can gain benefits from improvements of coordination between parties, customer-supplier relationship, risk management, flexibility and adaptability of the business, etc. (Supply chain council, 2012). Cheng et al. (2010) explained that the SCOR framework provides a systematic approach to manage and evaluate a complex supply chain of an organization. The model helps a user to integrate processes of reengineering, benchmarking, and process measurements (Garcia, 2009). The codification was standardized and included in the SCOR framework. In the year this research was conducted, the SCOR model had reached the thirteenth version with additional practical issues and applications.

Considering contents of the SCOR model, a supply chain perspective was divided into four hierarchical levels as illustrates in Figure 2.6. The top level considers all processes and flows in a supply chain, while the bottom level considers minor activities in a bottom-up approach. However, the bottom level is excluded from the SCOR scope, as it focuses to very details of each activity.

	Level		Examples	Comments
	#	Description		
Within scope of SCOR	1	Process Types (Scope)	Plan, Source, Make, Deliver, Return and Enable	Level-1 defines scope and content of a supply chain. At level-1 the basis-of-competition performance targets for a supply chain are set.
	2	Process Categories (Configuration)	Make-to-Stock, Make-to-Order, Engineer-to-Order Defective Products, MRO Products, Excess Products	Level-2 defines the operations strategy. At level-2 the process capabilities for a supply chain are set. (Make-to-Stock, Make-to-Order)
	3	Process Elements (Steps)	• Schedule Deliveries • Receive Product • Verify Product • Transfer Product • Authorize Payment	Level-3 defines the configuration of individual processes. At level-3 the ability to execute is set. At level-3 the focus is on the right: • Processes • Inputs and Outputs • Process performance • Practices • Technology capabilities • Skills of staff
Not in scope	4	Activities (Implementation)	Industry-, company-, location- and/or technology specific steps	Level-4 describes the activities performed within the supply chain. Companies implement industry-, company-, and/or location-specific processes and practices to achieve required performance

Figure 2.6: SCOR process model (Supply chain council, 2012)

Based on the SCOR model, its standard consists of five topics: performance, processes, practices, people, and special applications. Each topic can be explained briefly as follows.

i) Performance

Performance includes various techniques and metrics to assess overall supply chain performances of an organization. The assessment metrics were further categorized into five attributes: reliability, responsiveness, agility, cost, and asset management efficiency.

ii) Process

Process defines major processes in a supply chain. The SCOR model categorized processes into six types: plan, source, make, deliver, return, and enable.

- Plan includes all planning activities to balance resources and requirements, such as procurement plan, production plan, transportation plan, etc.
- Source includes all activities to obtain raw materials or services. It can be further categorized into stocked product, make-to-order product, and engineered-to-order product.
- Make includes all activities to converts raw materials to finished products. It also includes activities for manufacturing preparation and service. Make process extends from schedule production to waste disposal.
- Deliver includes activities to transport and distribute finished products to a customer.
- Return includes activities of receiving return finished product, disqualified materials, and customer support. It is categorized into source return and deliver return.
- Enable includes the overall management of supply chain, such as supply chain network, supply chain contracts, supply chain information, etc.

Figure 2.7 illustrates an overview of six SCOR processes. Plan process must be considered in an organizational level, while other processes can be considered within an organization.

Figure 2.7: SCOR major management processes (Supply chain council, 2012)

iii) Practices

Practices categorized working techniques in a supply chain into four types: emerging practice, best practice, standard practice, and declining practice. Brief concept of each practice was explained and connected to supply chain processes. Examples of practice are Just-in-time production, lean concept, logistic warehouse and planning, RFID, 3D printing, and Kanban.

iv) People

People deals with various skills of labor in a supply chain. The competency of skills were divided into five levels: novice, beginner, competent, proficient, and expert. These skills were categorized and explained briefly.

v) Special application

Special application explained environmental issues related to supply chain management. Some metrics were proposed for an environmental assessment, such as percentage recycle waste, carbon footprint, and emission rate. (Supply chain council, 2012).

2.3.3 Supply chain assessment

Chou (2004) investigated a supply chain performance measurement system. Balance scorecard, Total Quality Management (TQM), and SCOR model were studied as fundamental knowledge of the research. A framework for a supply chain measurement was proposed and implemented in a retail industry. From the research, a set of performance metrics were obtained with six considered criteria. The auther stated that the proposed systematic measurement system was proven useful to evaluate a supply chain performance. Ideally, a supply chain measurement system should be developed particularly for each company.

Lankford (2004) divided a supply chain assessment framework into three categories: efficiency, responsiveness, and effectiveness. Efficiency focuses on the minimization of costs, such as inventory reduction, increasing turnover rate, etc. Responsiveness focuses on a loss reduction, such as loss from market changes, loss from customer changes, etc. And, effectiveness focus on the process to manage assets efficiently.

Analytical Hierarchy Process (AHP) and Fuzzy Analytical Hierarchy Process (FAHP) concepts can be used to assess performances of a supply chain. AHP has an ability to prioritize supply chain scores from different interviewees, while FAHP provides an accuracy to weight supply chain factors. An accuracy for a supply chain performance assessment can be improved by including fuzzy sets in these assessment factors (Ponhan et al., 2012)

SCOR model version 11.0 included various supply chain performance assessment attributes. It explained different assessment attributes, required data, metrics, and equations. The relationships between performance, processes, and practices were included and mapped as a guideline for implementation. The attributes were categorized into five types: reliability, responsiveness, agility, costs, and asset management efficiency. They can be assessed and benchmarked to determine improvements of supply chain performances.

i) Reliability

Reliability is an ability to fulfill customer's order perfectly considering quality and timeliness. It considers a perfect order fulfillment score for an assessment. In general, this assessment attribute requires recorded statistics, such as quantity of defected products, quantity of total products, quantity of accurate documentation, and quantity of extra material consumption. for an assessment. The higher percentage of reliability indicates high supply chain performance of an organization.

ii) Responsiveness

Responsiveness is used to assess a cycle time required for each activity in a supply chain. The SCOR model defines a framework for cycle times and connected it to supply chain processes (e.g., source cycle time, make cycle time, and deliver cycle time). However, plan cycle time was not included in the framework. The assessment data can be collected from time sheets, production scheduling plan, project master plan, etc.

iii) Agility

Agility is used to assess an organization capability to respond to environmental changes. It consists of four major components: upside flexibility, upside adaptability, downside adaptability, and value at risk. An agility framework is proposed with a standard duration for an assessment, which can be adjusted accordingly. The data required for agility assessment can be obtained from recorded statistics of a company.

- Upside flexibility is a time required to achieve twenty percent improvement of a specific task, for example, the number of days required to increase twenty percent of an unplanned production.
- Upside adaptability is an ability to maximize outcomes of a specific task within thirty days, for example, maximum amount of resources that can be acquired within thirty days.
- Downside adaptability is an ability to minimize outcomes of a specific task in thirty days without penalties, for example, the maximum reduction in production that can be achieved in thirty days without cost penalties.
- Value at risk is the product of probability of risk event and monetized impact of that risk. The sum of risk in each process can indicate a supply chain risk of an organization.

iv) Costs

Costs provides cost assessment framework for each activity in a supply chain process. It is categorized into seven types: planning cost, sourcing cost, production cost, order management cost, fulfillment cost, return cost, and cost of goods sold. The data required for cost assessment can be obtained from financial documents, such as bill of quantities, payments, employee wages, etc.

v) Asset management efficiency

Asset management efficiency is used to assess an overall efficiency of a supply chain compared to a value of its available assets. It consists of three components: cast-to-cast cycle time, return on supply chain fixed assets, and return on working capital. The assessment is performed in an annual basis at a company level (Supply chain council, 2012).

2.3.4 Construction supply chain management

The construction supply chain can be defined as "A series functional activities, taking owner's perspective and requirements as objectives, begin with project requirements, then defining the project, financing the project, designing the project, constructing the project, handling over the project, maintaining the project until reconstruction or demolish session" (Ren, 2012).

"Supply chain management had been undervalued subject in the construction process" (Nummelin et al., 2011). There are difficulties for implementing supply chain management in construction industry. The basic supply chain principles were lacked in industrialized construction, which has long and complex supply chain (Vrijhoef and Koskela, 1999). These problematic issues were caused from a complex nature in construction, such as the variation of stakeholders between projects, time constraints, unique outcomes for different projects, limited resources, and involvement of many parties.

Figure 2.8 illustrates different dimensions of the construction supply chain from an industrial perspective. There are contractual relationships between stakeholders from the same construction project. The horizontal axis connects stakeholders from different tiers, while the vertical axis indicates available options of stakeholders in a supply chain. Overall, the study of a construction supply chain provides an understanding of the complexity in this industry (O'Brien et al., 2002).

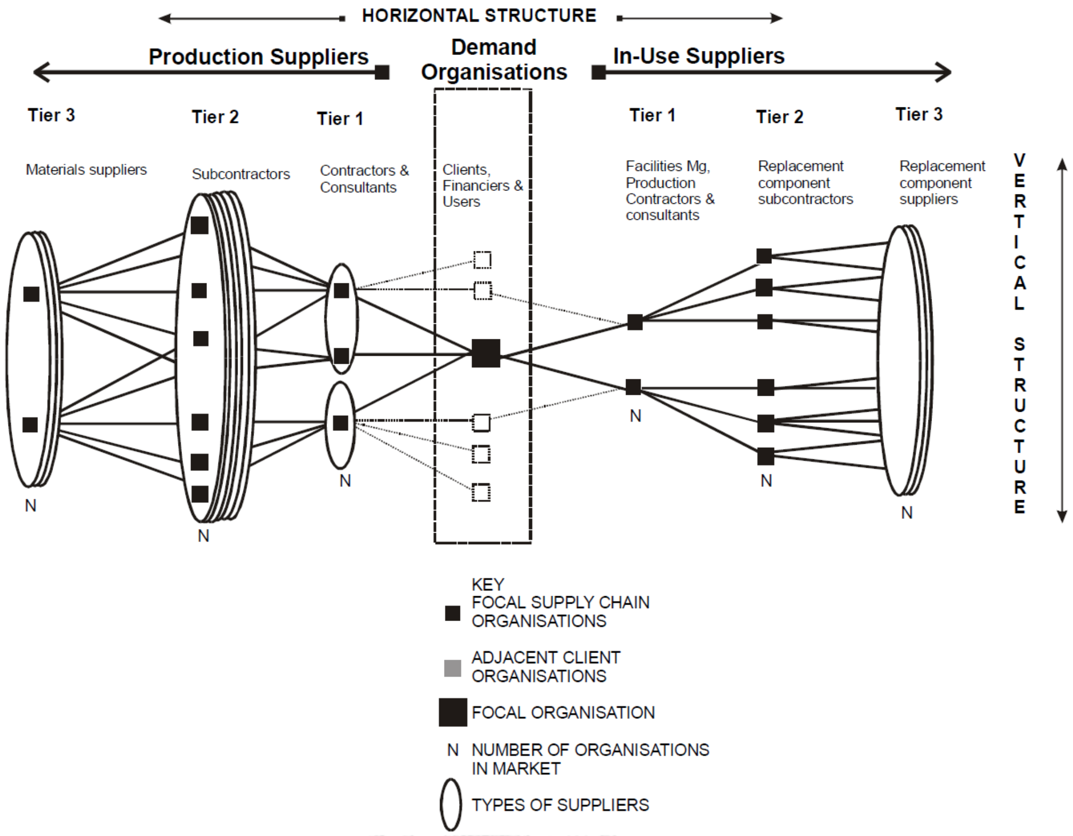

Figure 2.8: Construction supply chain structure from an industrial organization perspective (London et al., 2000 after Lambert et al., 1998 cited in O'Brien et al., 2002)

As supply chain management was originated for a manufacturing industry, its applications for a construction industry differ considerably. Vrijhoef and Koskela (1999) researched roles of supply chain management in a construction industry. The study was divided into four areas: the impact of supply chain on activities, the supply chain itself, the transferring activity, and the management of the supply chain. The different benefits from these areas, such as lead time reduction, better flow of material and labor, were determined and analyzed. The author stated that construction wastes are caused from using a traditional management system. The implementation of supply chain management can benefit overall processes of a construction management in long terms.

Tommelein and Arbulu (2002) explained differences between the traditional managerial approach and supply chain managerial approach in construction. Table 2.5

compares the differences between traditional and supply chain approach. It is obvious that supply chain approach is superior to traditional approach in most directions.

Karataş (2009) investigated the significance of supply chain management for contractors. The relationships between contractors, suppliers, and clients were investigated and analyzed. The author stated that, for the relationship between supplier and contractor, the most influential factors are the reliability of the delivery date, service quality, accurate order fulfillment, quality of material, and trust respectively. The implementation of supply chain management can improve efficiency and productivity between construction stakeholders. Nevertheless, the nature of construction prevents supply chain advancements. The biggest barriers for a supply chain integration are bidding process, late and incorrect payment, traditional contract, and unrealistic schedule.

Table 2.6: Traditional vs. supply chain managerial approach in construction (Tommelein and Arbulu, 2002)

Traditional Managerial Approach	Supply-chain Managerial Approach
Project-based Management	Supply-based Management, leveraging needs for multiple projects
Separation of Design, Fabrication, Construction/Installation, and Operation Functions	Total Life-cycle Management
Uniquely Engineered Facilities and Components	Assembly of Unique Facilities from Standardized Modules and Components
Liquidated Damages	Target Costing and Problem Solving through Strategic Alliance for Key Products and Components
Competitive Bidding	Emphasis on Long-term Working Relationships
Information Hoarding	Extensive Use of Communication and Information Technology to Create Information Visibility so that the Value Chain Supports the Supply Chain
Late Payments and Retainers	Prompt Payment to Minimize Cost of Capital (Time Value of Money is an Inventory Cost)
Long and Uncertain Lead Times with Extensive Use of Expediting	Short and Reliable Cycle Times from Raw Materials to Site Installation
Early Delivery of All Materials to the site	Phased Delivery of Materials to the Site to Match Installation Rates

Risku and Kärkkäinen (2004) stated that a construction logistic gained difficulties due to an increment in flexibility of a new project management method. It resulted in an increment of scheduling time of a construction supply chain.

Ericsson (2001) developed a simulation model for a construction supply chain. Based on a supply chain principle, the proposed model was divided into two parts: process simulation and project simulation. The process simulation focused on activities which are repetitive in nature, while the project simulation focused on a whole project or major parts of a construction. After simulations, the author concluded that the simulation model gives maximum benefits for cyclical operations. The scheduling and procurement process can be improved with a shorter duration for an analysis.

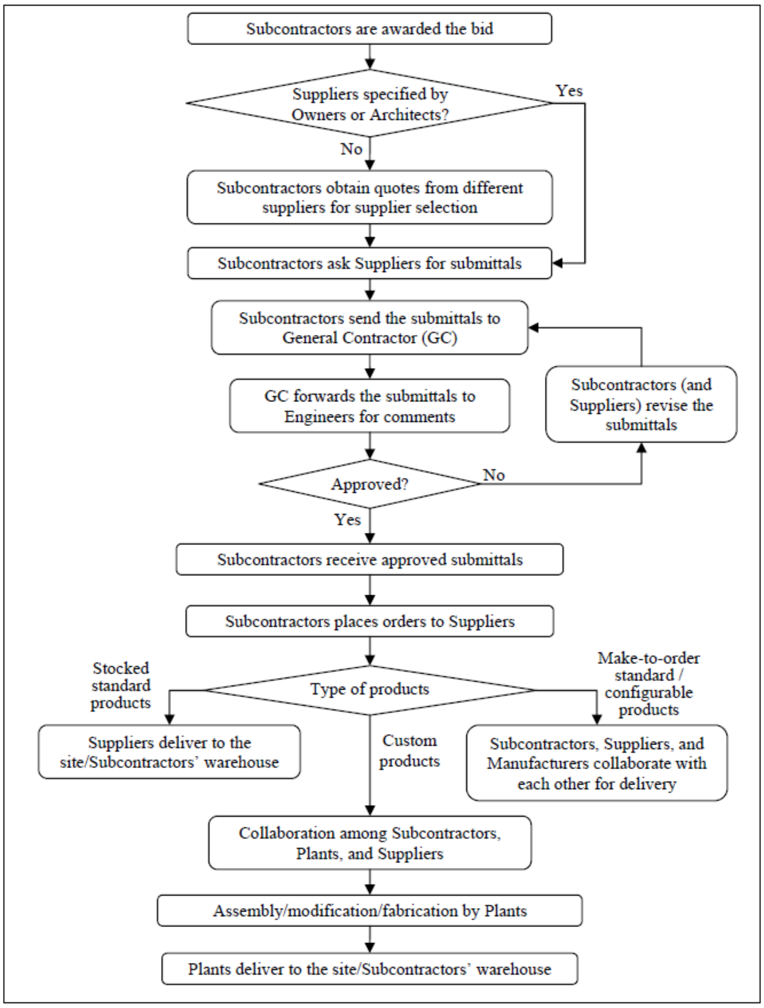

Figure 2.9: Flow chart of a typical material planning, procurement, and delivery management process in construction projects (Cheng et al., 2010)

Cheng et al. (2010) developed a flowchart to explain relationships in planning, procurement, and delivery methods for four construction stakeholders: general contractor, subcontractor, supplier, and engineer. Figure 2.9 illustrates an example of process flows from material procurement to delivery in a construction project.

Maturana et al. (2004) researched subcontractor management and evaluation for a construction supply chain. The author stated that collaborations in a supply chain is the key to reduce uncertainties from a supply chain. With a proper subcontractor collaboration, overall performance of a construction project can be improved accordingly.

2.3.5 Supply chain management for precast concrete

Limsupreeyarat (2005) stated that losses between supply chains of different organizations are major problems that reduce a construction productivity. For example, there are losses between precast concrete contractor and general contractor in nature. This loss is often negligible from the stakeholders and causes long term problems in a supply chain.

Constructing Excellent (2004) encouraged construction firms to implement a supply chain system. The benefits of construction supply chains are listed as follows.

i) Reduce real cost
ii) Remove wastes from the processes
iii) Reduce risks, increase certainty
iv) Improve the value of delivery
v) Enhance confidence in long term planning
vi) Establish long term relationship with the key client

Gilaninia et al. (2011) explored impacts of Information Technology (IT) on supply chain performances. The supply chain performances were derived by determining supply chain responsiveness and efficiency. The authors stated that an effective information sharing is a key for an organization to improve supply chain performances. The advancement of information technology definitely leads to overall change in supply chain management.

Khosrowshasi (2011) distinguished communications between the supply chain system and BIM-based supply chain system. Figure 2.10 illustrates supply chain and BIM-based supply chain communications.

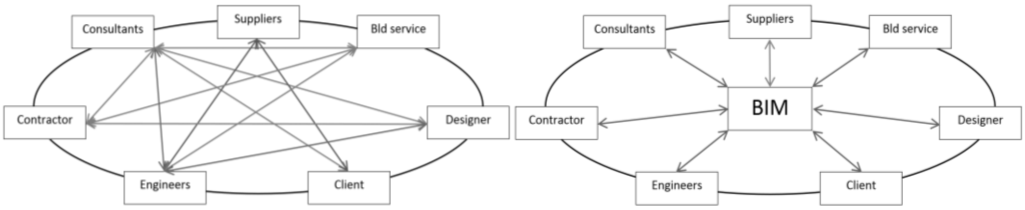

Figure 2.10: Supply chain and BIM-based supply chain communication (Khosrowshasi, 2011)

Considering a supply chain system for precast concrete contractor, a simplified diagram of the relationship can be centralized as illustrated in Figure 2.11. BIM can centralize the tasks for precast concrete contractor, client, and suppliers to improve supply chain collaboration. An internal collaboration can also be achieved by using BIM.

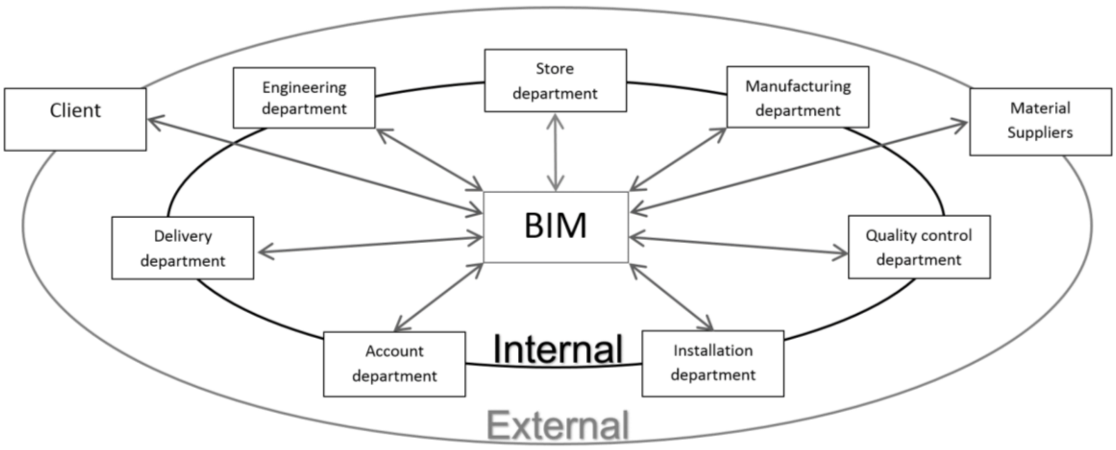

Figure 2.11: BIM-based supply chain for precast concrete contractor (modified after Khosrowshasi, 2011)

2.3.6 Limitations

Ren (2012) researched a lean concept for a construction supply chain. The author categorized problems related to a construction supply chain into seven interfaces: client/design, design/engineering & technique, engineering/purchasing &

installation, purchasing & preparation/subcontractor or supplier, supplier/subcontractor or site, subcontractor/site, and completion of a building. Based on the classification, precast concrete contractor problems are related to the fourth and fifth interfaces, which are inaccurate data, insufficient information, changes, untimely delivery, defective product, and long storage periods.

Theoretically, a long term relationship must be established between construction stakeholders to improve supply chain performances. However, it is impractical to establish long term relationships with every member in a construction project. The long term relationship should start with critical stakeholders, such as main suppliers, main sub-contractors, and main suppliers (Constructing Excellent, 2004).

Delay in decision making also causes losses in a construction supply chain. It can be minimized by using quick response and quick decision making technique (Limsupreeyarat, 2005).

To manage material shortage in a precast concrete supply chain, Ko (2013) developed a mathematical model for transshipment strategies. From the simulation, the transshipment management is not always beneficial. The author explained that a larger supply chain network can reduce the material shortage in a precast concrete supply chain.

2.4 Summary

From the literature review, it was found that BIM research projects were mostly focused on main contractor and designer perspectives. There have also been a limited number of BIM projects for precast concrete contractors. The research projects concerning an information management in a supply chain were scarce. There were conceptual ideas of an integration between BIM and a supply chain, which lacks of an actual practice. Therefore, there was a room left for the research project that integrate BIM to a supply chain of precast concrete contractors.

CHAPTER III
RESEARCH METHODOLOGY

This research is an experimental research, which entails five steps of literature review, instrumentation, experiment, analysis, and conclusion. The research methodology was designed to study the improvements of a precast concrete supply chain resulting from BIM implementation. It also focused on BIM documentation outcomes for precast contractors.

This chapter has three main purposes: to describe the research methodology, to explain the instrumentation process, and to explain the implementation and data collection processes.

3.1 Research Procedure

The procedure of this research project is divided into nine main steps as illustrated in Figure 3.1.

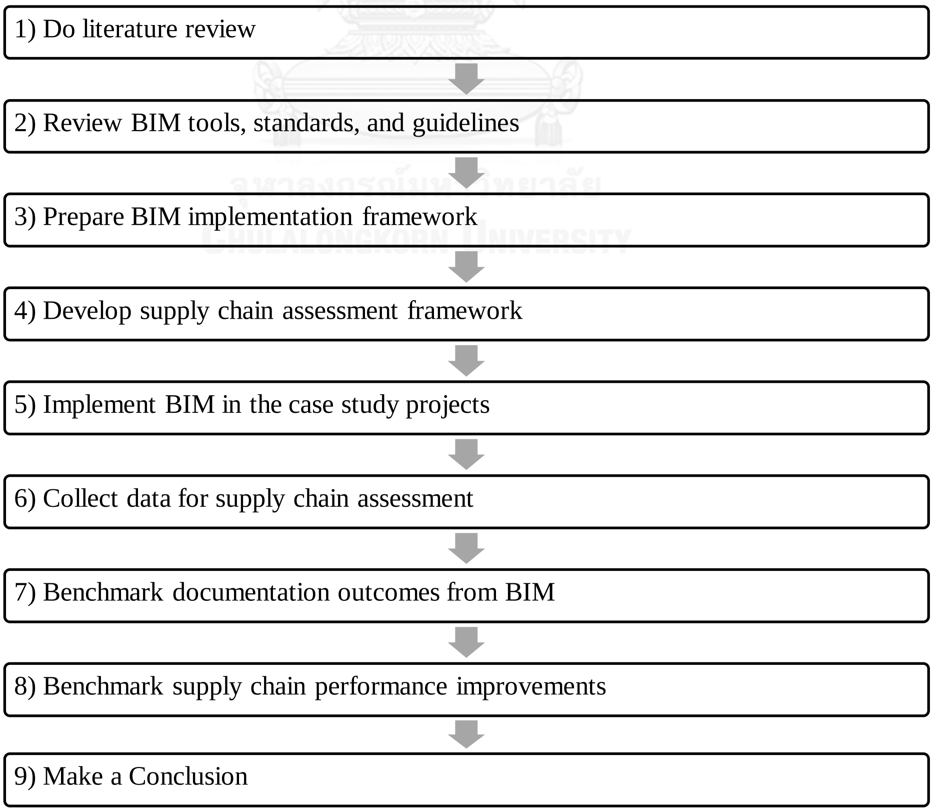

Figure 3.1: Research steps

3.2 Do Literature Review

The first step of this research project is to do the literature review. It has the main objective to collect relevant knowledge including the state-of-the-art of research subjects. The researcher was required to review old literatures on four major topics: Building Information Modeling (BIM), supply chain management, precast concrete, and supply chain assessment framework.

BIM and precast concrete topics were selected and studied, as they were major concerns of this research project. Old projects concerning BIM and precast concrete received first priority for the review. The concept of supply chain management was included as it provides a framework for precast concrete processes. Also, assessment frameworks were studied to determine a proper solution to evaluate improvements resulting from BIM implementation.

3.3 Review BIM Tools, Standards, and Guidelines

BIM software (or) BIM tool was another key for BIM implementation. The researcher was required to review various BIM tools to identify their potentials for precast concrete tasks. In the year this research was conducted, BIM was very new to a precast concrete industry in Thailand. It was difficult to find a case study company with an experienced BIM modeler. Due to this limitation, the researcher was required to attend trainings to gain technical knowledge of a BIM tool and substitute BIM modeler tasks. Then, the researcher must selected a suitable tool based on the availability in Thailand (e.g., Autodesk Revit from Autodesk, and Tekla Structure from Tekla Corporation). Some BIM tools were excluded to avoid the copyright infringement issues.

The researcher preferred Autodesk Revit as a main tool in this research project, because the software has three-dimensional modeling flexibility with basic functions for precast concrete tasks. There is an education version of the tool available for a research purpose. Also, a user interface (UI) of this tool is user-friendly and has high potential for the development in future.

There were variety of BIM standards and guidelines available for BIM implementation such as national BIM standard (NBIM), Singapore BIM guide, and UK BIM standard. These standards provide applicable references for the study. The Information Delivery Manual (IDM) for precast concrete was studied as a guideline for implementation.

3.4 Prepare BIM implementation framework

i) Select a qualified case study company

The researcher had defined major criteria for BIM implementation before selecting a precast concrete case study company. The main criteria were type of precast concrete factory, variety of precast products, availability of equipment, availability of data, and service of precast concrete design. Then, the researcher requested the qualified company for a participation. It was very important to determine a case study company with good cooperation for a data collection process.

ii) Investigate current practice of the case study company

As actual practices differ between companies, an investigation was required to determine the current practice of the case study company. Three precast concrete projects were selected as pilot case study projects for investigation. Basic interviews were conducted to study practices, responsibilities, information exchanges, and problematic issues. There were five major documentation outcomes to be achieved from BIM: production drawing, assembly drawing, estimation sheet, reinforcement cut list, and schedule. The information exchanges and relationships of the outcomes were mapped and studied. The knowledge obtained from this step was used to develop a preliminary framework for BIM implementation.

iii) Prepare a BIM model development process

After obtained sufficient information, the information items were tabulated and prioritized. The information exchanges were mapped to define the flows between different activities. The qualified information items, such as specifications, schedules, etc., were prepared and included in a BIM model. It was important to design the flows of information properly to simplified working processes and maximize BIM benefits.

As BIM tools were not designed for production tasks, the researcher had to develop specific flows to create an applicable precast concrete BIM model. Then, automations were designed for precast concrete tasks, for example, to calculate the weight of a concrete product automatically, etc. The database was developed specifically for the information of the case study company. Finally, the database was tested for several times before an actual usage.

After this step, a specific process required to develop a BIM model for precast concrete was obtained with BIM database for an implementation.

3.5 Develop Supply Chain Assessment Framework

A proper assessment framework was required to determine supply chain improvements resulting from BIM. For this research project, Supply Chain Operations Reference (SCOR) model was preferred as a guideline to determine improvements from BIM. The SCOR standard provides five assessment attributes, which some of them are unsuitable and unrelated to BIM. Therefore, some SCOR assessment attributes must be adjusted to fit the characteristics of a precast concrete supply chain. Although the SCOR model can assess a whole precast concrete supply chain, this research project concerned only processes associated with BIM implementation. Irrelevant processes were excluded from the assessment.

3.6 Implement BIM in the Case Study Projects

BIM implementation was designed as an experiment to determine differences between conventional and BIM-based processes. Both processes must be performed in parallel on the same project. For consistency, it was required to implement BIM on two case study projects of the same scale. Two precast concrete housing projects were preferred with multiple types of precast concrete products. Then, BIM models were developed in parallel to a conventional process. Some data, such as the duration of each activity, were recorded during an implementation period. After the implementation, five major outcomes were generated from the BIM model for comparisons.

3.7 Collect Data for Supply Chain Assessment

i) Collect data by recording

During the implementation period, it was necessary to record the time spent for each activity in design and planning processes. Time sheets were developed for both conventional and BIM-based processes. The responsible units were required to record time spent for each task for both case study projects.

ii) Collect data using in-depth interviews

The in-depth interview technique was preferred for two main reasons. First, the technique can access to detailed qualitative data, which were required for a quality assessment. Second, the technique has high flexibility for a data collection process. BIM opportunities for precast concrete tasks can be further clarified. The interviews were conducted individually with three experts of the case study company. The data were recorded using an audio recording and a field note. In addition, the open-ends questions were used to obtain opinions towards BIM.

iii) Collect data by estimating

Most of financial data were unavailable for an assessment as they are confidential to the case study company, such as labor wage and reward. These data must be estimated based on relevant factors, such as standard wage in the market, the year this research was conducted, etc. These data belongs to the cost assessment in a supply chain.

3.8 Benchmark Documentation Outcomes from BIM

After BIM models were completed, five major outcomes were generated from BIM models for a documentation process. The documentation outcomes between conventional and BIM-based processes were benchmarked, for example, the material quantity generated from BIM must be compared with the material quantity calculated from a conventional process to determine the accuracy. Besides outcome comparisons, the development processes must also be compared to determine overall improvements.

3.9 Benchmark Supply Chain Performance Improvement

After BIM implementation, the supply chain performances were benchmarked and analyzed. Based on the modified SCOR assessment framework, four attributes were selected for the assessment. The results of supply chain cost and time were calculated to determine percentage improvements. The factors affected supply chain cost and time were analyzed and explained. For supply chain reliability and agility, each component was explained with problematic issues and achievable improvements from BIM implementation. The benefits and drawbacks were summarized in details. Based on the hypothesis, BIM can maximize benefits directly for a make process as it is directly related to design and planning processes. For a deliver process, it can gain indirect benefits from BIM.

3.10 Make a Conclusion

After the supply chain performance analysis was completed, the research work was concluded. The improvements resulting from BIM were summarized and explained in details with limitations. Finally, the suggestions were included for research projects in the future.

CHAPTER IV
BIM IMPLEMENTATION FRAMEWORK

This chapter presents a BIM implementation process for precast concrete contractors. The chapter consists of five sections: preliminary investigation (section 4.1), BIM model development for precast concrete structures (section 4.2), information database development (section 4.3), major outcomes from BIM model (section 4.4), and summary (section 4.5).

4.1 Preliminary Investigation

An appropriate BIM model development process must be prepared to implement BIM in an organization efficiently. In general, a BIM model can be developed based on functions and systems of a BIM tool. Knowledge for a BIM model development is commonly prepared by software companies, which mostly focus on tasks in construction.

Precast concrete contractors require different outcomes from BIM since precast concrete contractors are responsible for design, production, and erection. BIM models development process must be designed specifically to obtain required outcomes for precast concrete tasks. Therefore, a specific BIM model development process for precast concrete contractors is required before implementing BIM in a case study company.

The selected case study company is one of the largest precast concrete contractors in Bangkok with 40 years of establishment. The company provides three types of precast concrete products: made-to-stock, made-to-order, and engineered-to-order. The product includes footing, beam, column, wall, pipe, stair, tray, and hollow-core slab. The company is highly experienced, as it has high potential to manufacture complex products such as waffle wall and curved stairs.

In addition to a mass production, the company also focuses on a customized production such as a unique precast concrete house. The product design, which was a critical criterion for the case study company selection, is provided as a service of the company.

The organization structure and information exchanges between working units of the case study company were analyzed. From paper-based documents, the critical information items were recorded, prioritized, and selected for implementation. Table 4.1 shows examples of information items obtained from various documents, which are categorized into four groups: general information, design information, production information, and delivery information.

As can be seen, the information items are classified into three types: compulsory, optional, and not included. The compulsory information items such as specifications and schedules are vital to main processes and must be included in BIM models. The optional information items such as production location and approval signatures can be included in BIM models to improve the levels of detail. This information can also be processed in paper-based documents without BIM. The last type of information items is not included, as they are not related to BIM directly. Financial information and contractual information are examples of the exclusions. In addition, the modes of information items can be classified into digital-based document, paper-based document, and verbal communication. Ideally, all BIM information items must be processed using digital-based documents, which are hardly possible in the beginning of a BIM adoption phase.

Finally, these information items are used to design information flows for a precast concrete BIM model development.

4.2 BIM Model Development for Precast Concrete Structures

In general, there are three major components of precast concrete products: concrete, reinforcement steel bars, and embedded parts. A BIM model must be designed to include these components and utilize information systematically. Based on the functions of Autodesk Revit, there are various options to create a BIM models for precast concrete structures. Among these options, the outcomes generated from BIM models differ considerably, which some of them are inapplicable. It is important to determine an optimal model development process to maximize BIM benefits for precast concrete tasks.

Table 4.1: Example of information items for BIM model development

No.	Information Items	Descriptions	BIM Inclusion
General Information			
1	Date of order	The date that a precast concrete contractor received a	Compulsory
2	Project name	Name of a construction project	Compulsory
3	Type of structure	Type of a project structure	Compulsory
4	Project address	Address of a construction site	Compulsory
5	Client name	Name of a client	Compulsory
6	Client contact	Contact of a client	Compulsory
7	Unit price	Unit price of a single product	Not included
8	Total price (with VAT)	Total price with value added tax (VAT)	Not included
9	Terms and conditions	Terms and conditions stated in purchase order	Not included
10	Signature	Signature of authorized person for purchase	Optional
	…	…	…
Design Information			
1	Project ID	An ID of a project named for management	Compulsory
2	Production drawing	Graphical information of a precast product	Compulsory
3	Assembly drawing	Graphical information of assemble precast products	Compulsory
4	Concrete specification	Specification of concrete, such as strength, slump, etc.	Compulsory
5	Reinforcement	Specification of reinforcement steel bar, such as size,	Compulsory
6	Stirrups specification	Specification of stirrups, such as size, shape, quantity,	Compulsory
7	Embedded parts	Type and specification of various embedded parts	Compulsory
8	Signature	Signature of authorized person for production	Optional
9	Remarks	Miscellaneous information	Optional
10	Structural analysis	Structural calculation for precast products	Not included
	…	…	…
Production Information			
1	Production drawing	Graphical information of a precast product	Compulsory
2	Concrete specification	Specification of concrete, such as strength, slump, etc.	Compulsory
3	Reinforcement	Specification of reinforcement steel bar, such as size,	Compulsory
4	Stirrups specification	Specification of stirrups, such as size, shape, quantity,	Compulsory
5	Embedded parts	Type and specification of various embedded parts	Compulsory
6	Production location	Location for production activities	Optional
7	Production team	Labor team assigned for production	Optional
8	Production equipment	Equipment assigned for production	Optional
9	Production sequence	Sequence of each product for production	Compulsory
10	Production schedule	Time schedule for production	Compulsory
	…	…	…
Delivery Information			
1	Driver name	Name of the driver assigned for transportation	Optional
2	Vehicle ID	ID of the vehicle assigned for transportation	Optional
3	Delivery ID	ID of the trip for transportation	Compulsory
4	Sequence	Transportation sequence for each precast product	Compulsory
5	Weight	Weight of all products in a trip	Compulsory
6	Assembly drawing	Graphical information of assemble precast products	Compulsory
7	Product weight	Weight of each precast product required for lifting	Compulsory
8	Erection team	Labor team assigned for erection	Optional
9	Sequence	Erection sequence for each precast product	Compulsory
10	Schedule	Time schedule for erection	Compulsory
	…	…	…

There are four major concerns before developing a BIM model for precast concrete contractors: outcomes which can be obtained from a model, benefits from a BIM tool, simplicity of a model, and ability to improve the model in the future. After trial and errors, a BIM model development process for precast concrete structures can be categorized into three options.

i) Option 1: Model precast concrete structures directly in a project level

Precast concrete BIM models can be developed using common functions of structural components such as concrete beams, concrete slabs, and concrete columns. These structural parts are disassembled at both ends to create three-dimensional precast products. The reinforcement steel bars and embedded part are modelled directly in a project. This modeling process is very simple and fast. However, BIM models obtained from this option can be limitedly used because the level of detail is too low (LOD 100). It is impossible to perform quantification, interference detection, and parametric calculation. Furthermore, the model can not be utilized as a database for future projects. Although the development process is simple and fast, the outcomes obtained are inapplicable. As a result in this research, this option for BIM model development was not considered.

ii) Option 2: Create a database for precast concrete products

Information of precast concrete products were categorized and prepared in a database. To develop a BIM model, the product information are selected and adjusted to the requirements using prepared parameters, such as length, width, and thickness. The graphical information of precast concrete products is adjusted to these parametric inputs. Then, the products are transferred into a project to form a precast concrete structure. The reinforcement steel bars and embedded parts are added at the end to complete a precast concrete BIM model.

Using this process, universal precast concrete products can be developed and stored as a database. Although this option requires time for database preparation, the model development process is fast and systematic. Three-dimensional clash detection can be performed to determine interferences between products. The level of detail of BIM model can reach 250. However, BIM models developed from this option is not applicable to perform parametric calculation, automated annotation, and detailed quantification. Though precast concrete structures can be modeled properly, BIM benefits are not yet maximized. Many tasks must be performed manually. Therefore, this option was not considered in this research as it can not exploit full potential of the selected BIM tool.

iii) Option 3: Create a database for precast concrete products and embedded parts

For this option, precast concrete products and embedded parts were prioritized, categorized, and modeled separately in a database. The database must be properly prepared before developing a BIM model for a project. The duration required for database preparation depends on the variety of precast products and embedded parts. To develop a BIM model, the embedded parts are loaded into precast concrete products. The products are modified according to the design. After each precast concrete product is completed, it is transferred to the project to form a precast concrete structure. Finally, the reinforcement steel bars are modeled as a final component of a BIM model. Clearly, the preparation for this option is complex and time consuming. It also requires the expertise of BIM modelers. With a proper database, this option has the advantages as follows.

- Using a proper database, the model development process is highly systematic and fast.
- The quantification process can be fully automated with parametric calculations.
- Three-dimensional visualization generates in great details for the presentations.
- The interference detection can be performed in details, for example, the interference between embedded parts can be analyzed.
- Schedule and monitoring process can be managed with ease.
- The database is universal, which it can be reused for future projects.
- BIM model can be standardized to obtain the required outcomes.
- The outcomes obtained can reach to the level of detail of 350 to 400. This level of detail is sufficient enough to use for the production process.

BIM benefits can be maximized for managing a precast concrete supply chain. Though a significant amount of time is necessary for preparing the database, this model development process is the most favorable for this research. Table 4.2 compares the benefits from three options of BIM model development.

Table 4.2: Comparisons of benefits for different BIM model development options

No.	BIM Benefits	Option 1	Option 2	Option 3
1	Visualization	✓	✓	✓
2	Interference detection	-	✓	✓
3	Quantification	-	Partially	✓
4	Scheduling	-	✓	✓
5	Monitoring	-	✓	✓
6	Analysis	-	-	-
	Level of detail (LOD)	100	250	350 - 400

In addition, none of these model development options can perform a structural analysis for precast concrete structures due to limited time for development. It must also be noted that the finishing such as concrete surfacing, cement grouting, welding, and silicone injection was excluded from the three-dimensional model development because it requires to be mentioned only in text descriptions.

4.3 Information Database Development

The database development is the final part of BIM implementation framework development. The database development process was based on the selected BIM tool: Autodesk Revit. For the proposed model, the database is divided into three parts: product database, embedded part database, and project template.

To gather generic information of precast products, the design in old projects of the case study company were analyzed. Three precast concrete housing projects with seven types of precast concrete products (e.g., footing, beam, column, tray, wall, stair, and slab) were selected and studied as pilot case study projects. The information items for each product were tabulated and categorized.

4.3.1 Product database

The product database includes a set of graphical and non-graphical information associated with precast concrete products. The information of precast concrete products were further classified differently based on technical knowledge for product design of the case study company. For example, a precast concrete column was classified based on quantity of corbels, whereas a precast concrete beam was classified based on the connections at the ends. As there were multiple types of precast concrete products, automations were required to simplify working processes. The information items such as length, width, and thickness are stored in each product database with design equations for automations. Some of them were also connected to graphical outcomes of a BIM tool.

It is essential to design the flows of information effectively to maximize BIM benefits. Using parametric calculations, some information items can be generated from BIM models automatically. This automation process can directly eliminate errors from manual processes. For example, the weight of precast concrete products can be calculated automatically by multiplying concrete volume with a unit weight of concrete. When a product is modified to specific dimensions, the product weight is adjusted automatically for the delivery. Furthermore, the unit weight of concrete can be connected to a standard of concrete mix design to improve documentation accuracy. Overall, BIM automations designed for implementation are based on the requirements of the case study company. Some automations are designed with complex equations to generate graphical information, whereas some automations are designed with simplicity just to count an integer for quantification.

In this research, the product database for seven types of precast concrete products was prepared for implementation: precast concrete beam, column, footing, slab, stair, tray, and wall.

4.3.2 Embedded part database

The embedded part database encompasses embedded parts required for product design such as steel plate, angle bar, pipe, and flat bar. The embedded part database was developed in the same way as a product database, which was modeled according to the technical design of the case study company. The automation of embedded parts is simple because most embedded parts require simple adjustments in dimensions. After an embedded part database was prepared, it was transferred into its particular product database and stored for future usages. Figure 4.1 illustrates an example of information flows from information items of an angle bar to the database of a precast concrete beams.

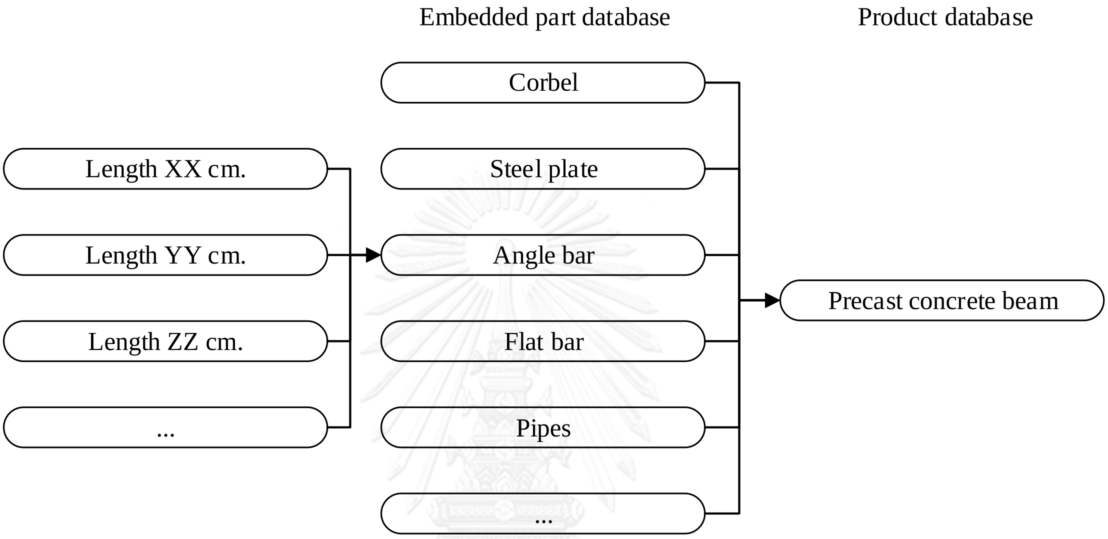

Figure 4.1: Information flows from a single information item to a precast concrete beam database

4.3.3 Project template

The project template includes reinforcement information, annotations, sheets, and other information required for documentation. The project template is used for three major purposes. First, it is used to standardize an appearance of the graphical outcomes, such as annotation of dimensions, text font and size, etc. Second, it includes specific information, such as a reinforcement database (e.g., size, shape, type, and bending radius). And third, it includes the pattern of information flows for documentation. For example, the product lists can be generated and sorted automatically using the template.

The project template was prepared accordingly to the product database and embedded part database to automate outcomes from BIM. Reinforcement bar information were prepared for rebar size, shape, and bending angle. For documentation, the template required to create paper-based documents were prepared for the size of A3 and A4, with the documentation styles of the case study company. Fonts and symbols were also prepared based on an actual practice of the case study company.

For quantification, tables were designed to create product lists, quantification sheets, schedules, and check lists. After a completion, the template was revised and tested properly before an actual implementation.

4.3.4 Hierarchy of information flows

After preparing the database, the flows of information from a single concrete product to form a precast concrete model can be mapped. The flows can be divided into three levels: embedded part database, product database, and project. Figure 4.2 illustrates an example of flows from an embedded part database of a precast concrete beam to a project.

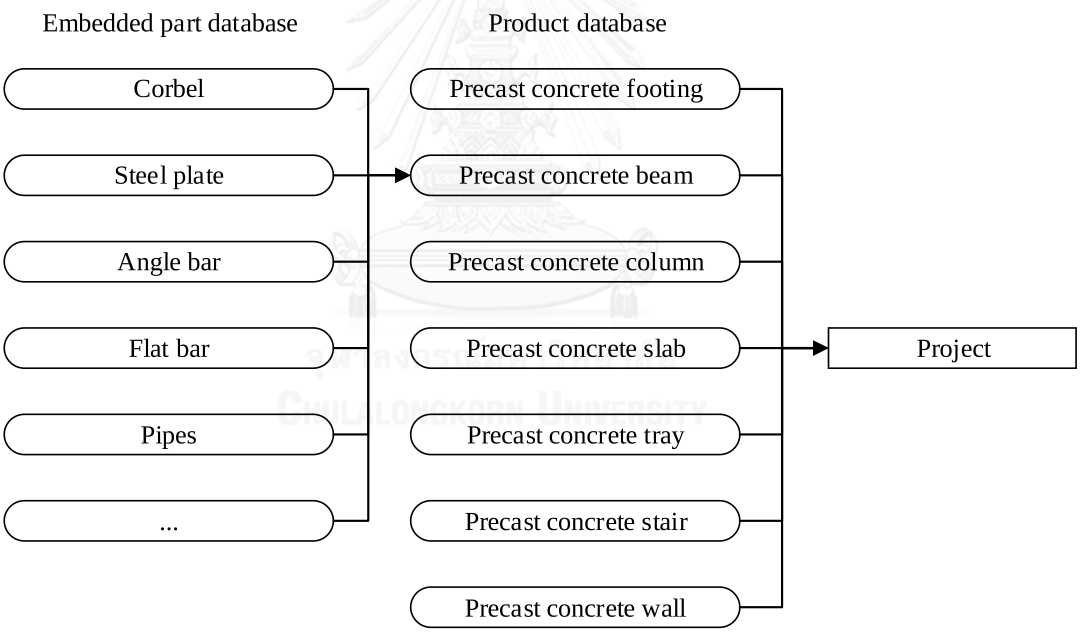

Figure 4.2: Information flows from embedded parts to a project

From Figure 4.2, an embedded part information of precast concrete beam flows to precast concrete beam database, which a beam also consists of different types of beam design. Each product stores different information of embedded parts according to the design. For implementation, the information of precast concrete beam can be selected together with required embedded parts. The shape and connection of precast concrete beam can be adjusted and selected to the requirements and transferred into the project. The process is repeated until full a precast concrete structure is assembled.

After all products are assembled in a project, the information of reinforcement steel bars are added. The template is applied to automate documentations. Figure 4.3 illustrates an example of information flows from a project template to a completed BIM model.

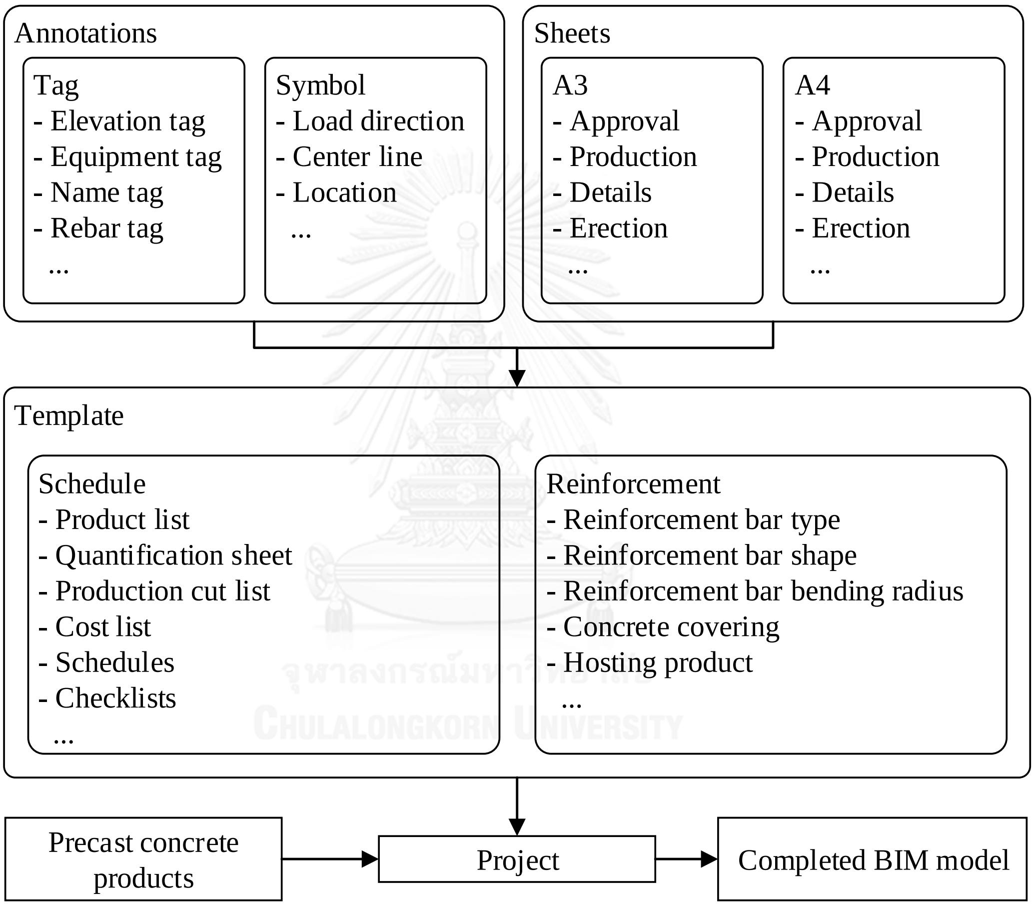

Figure 4.3: Information flows from project template to a BIM model

BIM model creation and utilization process can be summarized into five main activities as follows.

i) Create product models: to model three dimensional precast concrete products with embedded parts.

ii) Create an assembly model: to assemble product models and form a precast concrete structure in a project level.

iii) Create reinforcement bars: to create reinforcement steel bars for products.

iv) Create drawings: to group product components and create drawings.

v) Documentation: to prepare and manage documents generated from BIM model.

After BIM model is completed, the model can be utilized to create five major documentation outcomes of design and planning processes: production drawing, assembly drawing, quantification sheet, reinforcement cut list, and schedule. Figure 4.4 illustrates design and planning processes between conventional and BIM.

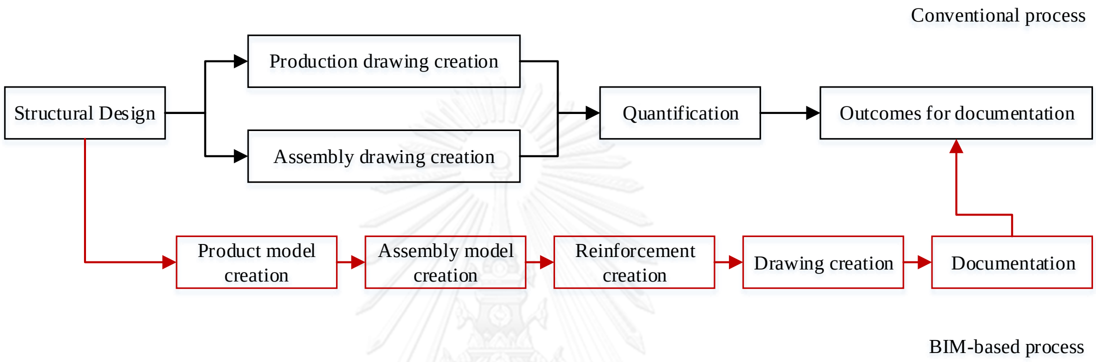

Figure 4.4: Conventional vs. BIM-based process

For a conventional process, both production drawings and assembly drawings are created in two dimensions in parallel to check the correctness of a design. After both drawings are completed, a quantification process is performed to create lists, schedules, and other documents from the design. The process is totally different from a BIM-based process which requires different modeling processes. For consistency, similar documentation outcomes are used to benchmark differences between these processes.

Also, it must be noted that BIM implementation process for this research project covered the product detailing part of precast concrete design as the BIM modeler does not have the knowledge of precast concrete structural analysis.

4.4 Major Outcomes from a BIM model

A BIM model for precast concrete contractors must be able to generate documents as the major outcomes from design and planning processes. Based on preliminary investigation, there were five major documentation outcomes required from a BIM model: production drawing, assembly drawing, estimation sheet, reinforcement cut list, and schedule.

i) Production drawing

A production drawing is the first outcome of design and planning processes. It is the most important document published for a precast concrete production. The drawing consists of detailed images of each precast concrete product, specifications, symbols, annotations, etc. The complexity of production drawing is directly related to the type of a product. Engineering-to-order products require very detailed production drawings, whereas made-to-stock products require only a standard for production.

ii) Assembly drawing

An assembly drawing is the second most important outcome from design and planning processes. It illustrates an assembly of precast concrete products to form a structure. This drawing includes images of a precast structure from different viewpoints and information for an erection process. The complexity of assembly drawing varies on types of precast concrete structure. It could be very simple for precast concrete slabs or very complex for members of a skeleton-frame structure.

iii) Estimation sheet

An estimation sheet is the third outcome from design and planning processes. It includes the quantity of each material required for production for different projects. In general, estimation sheets may be classified into 2 types: preliminary estimation and detailed estimation. A preliminary estimation sheet is created before a project acquisition to determine non-detailed cost for bidding. It is excluded from this research, as a BIM model requires time for development. A detailed estimation provides detailed information of each material requires for a project.

iv) Reinforcement cut list

A reinforcement cut list consists of shape, dimension, type, and quantity of reinforcement steel bars for each precast concrete product, which has some similarities with an estimation sheet. The major difference between estimation sheet and reinforcement cut list is the graphical information. The graphical information of reinforcement steel bars is required as there are varieties of steel shapes in a product such as L-shape, straight, and square. Before a production, this list must be completed and submitted for a material preparation. This document is usually prepared by an engineering unit or a production unit.

v) *Schedule*

Schedule is the last outcome from design and planning processes. In general, there are three major schedules published for management: production schedule, transportation schedule, and erection schedule. These schedules do not include only time parameters, but also various information for management, such as checklists, storage locations, transportation sequence, and remarks. The information in these documents are important for management through a supply chain. Production unit is responsible for a schedule creation.

4.5 Summary

This chapter presents BIM model development processes and an implementation framework for precast concrete contractors. Different BIM model development options are presented and compared to determine an optimal option for precast concrete tasks. The information flows for design and planning processes are explained with five major documentation outcomes expecting from BIM. From this process, the researcher gained the knowledge to develop a BIM model specifically for precast concrete contractors. The database was completely prepared for BIM implementation based on design information of the case study company.

CHAPTER V
DEVELOPING SUPPLY CHAIN ASSESSMENT FRAMEWORK

In this chapter, a SCOR modification process for an assessment is presented in details. The chapter has two major purposes: to describe the assessment framework selection and to explain the adjustments of assessment attributes. The chapter consists of seven sections: supply chain performance assessment framework (section 5.1), reliability (section 5.2), responsiveness (section 5.3), agility (section 5.4), cost (section 5.5), asset management efficiency (section 5.6), and summary (section 5.7).

5.1 Supply Chain Performance Assessment Framework

Besides a BIM model development process, this research project also requires a suitable assessment metrics to determine improvements of a BIM-based supply chain. In general, critical success factors of a construction project are used to evaluate and benchmark overall performances, resulting in a requirement of an assessment framework. Without a proper framework, the comparisons between conventional and BIM-based supply chains would be troublesome and inconsistent.

In the year this research was conducted, there were numerous frameworks available for a precast concrete assessment. However, most of the assessment frameworks, such as precast/pre-stressed concrete institute (PCI) standard, focused on a quality assessment instead of a supply chain assessment. The performances of a precast concrete supply chain can not be assessed from these frameworks.

The Supply Chain Operations Reference (SCOR) model provides a standard framework for a supply chain performance assessment. This framework is highly comprehensive, as it can be applied to different types of a manufacturing industry. However, the SCOR assessment framework is still inappropriate for this research project for two major reasons. First, as a precast concrete industry encompasses a discrete manufacturing, precast concrete products varies with comparatively less quantity for production. The SCOR assessment framework is inappropriate for customized production of precast concrete products. Second, this research focused on BIM implementation, which deals with an information management of precast concrete contractors. The SCOR assessment framework should be modified accordingly to focus on the interested subjects.

Therefore, the SCOR assessment framework is the best option available for this research project, but it still requires modifications to fit precast concrete characteristics. Based on the SCOR model version 11.0, there are five major attributes for the assessment: reliability, responsiveness, agility, cost, and asset management efficiency.

5.2 Reliability

Reliability is the first attribute of the SCOR performance assessment. It is used to determine an ability of an organization to fulfill customer orders perfectly in a supply chain. The major assessment component for reliability is called perfect order fulfillment. It is a percentage score of a perfect condition achieved on four components: production quantity, delivery condition, documentation condition, and product condition. Perfect order fulfillment can be considered as both quality and time assessment of a supply chain.

For a reliability rating system, a perfect order fulfillment can be evaluated by giving a score 1 for perfect condition and 0 for imperfect condition. Four components of a product are evaluated for a fixed period of production. Then, they are summed and averaged to determine a reliability score. The new percentage score is benchmarked with recorded scores to determine percentage improvement of reliability in a supply chain.

Reliability scoring system can not be applied directly to this research project because of three major reasons. First, a precast concrete industry generally encompasses a discrete production. It is inconsistent to compare different products directly, especially for the customized production of the case study company. Second, the quantity of a precast concrete production is comparatively low. The assessment requires a mass production for accurate results. And third, the recorded statistics of the case study company are required to benchmark reliability scores. The case study company was unable to provide these confidential data. Therefore, the data collection must be modified from quantitative to qualitative data with four similar components: production quantity, delivery condition, documentation, and product condition as major considerations.

The data collection process for reliability was performed by using in-depth interview technique with experts of the case study company. Before an interview, BIM outcomes and time sheets were presented and compared with outcomes from the conventional process. The assessment attributes were explained clearly with examples. During the interview, data were recorded using an audio recorder and a field note. The interviews focused on problematic issues and achievable improvements of BIM on four major components as follows.

- Perfect quantity
- Perfect delivery
- Perfect documentation
- Perfect condition

In conclusion, reliability assessment was modified to assess qualitative data of four major components of perfect order fulfillment. The data collection was performed by using in-depth interview technique on experts of the case study company. The data obtained were analyzed to determine reliability improvements for a BIM-based supply chain.

5.3 Responsiveness

Responsiveness is the second attribute of the SCOR performance assessment which deals with time in a supply chain. It is used to determine a speed of an organization to perform supply chain processes such as source, make, and deliver. For responsiveness, an order fulfillment cycle time is used as a major assessment component. It is the time required to fulfill the customer orders, which can be calculated by combining cycle times of all processes. The cycle time can be further categorized into three types: source cycle time, make cycle time, and deliver cycle time. Also, the cycle time can be separated into process time and dwell time. The process time is a productive time in cycle time, whereas the dwell time is a non-productive time.

In general, to assess responsiveness, new cycle times must be recorded and used to benchmark with old cycle times. This assessment is suitable for the repetitiveness of a mass production. This research project focused a supply chain time at a project level. Process times can be collected for both conventional and BIM-based processes on the same project without consistency issues.

BIM implementation affects a make process of a precast concrete supply chain directly, especially for design and planning processes. Though BIM has a potential to minimize times from improved information management and collaboration for deliver processes, their process times are related directly to tasks on an operational level. For example, a process time for transportation is based on traffic condition, distance of transportation, and maximum speed of vehicle. These factors are unaffected by BIM. Therefore, an assessment was focused on design and planning processes, which is a subset of a make cycle time. The process times between conventional and BIM-based supply chains were collected in details on two case study projects.

The data collection process for responsiveness must be performed separately for two processes. For a conventional process, a time sheet was prepared for responsible working units of the case study company, such as engineer, draftsman, and production manager. The time taken for each activity for the case study project was recorded in an hour basis. At the end of the project, these time sheets were collected for an analysis. For a BIM-based process, similar time sheets were used by the researcher to record the duration for each activity. Table 5.1 demonstrates a time sheet used for reliability data collection.

After BIM implementation was completed on two case study projects, the process times of conventional and BIM-based supply chains can be benchmarked for an analysis. The supply chain time improvements of can be determined from this assessment. It must be noted that the total times can be benchmarked only at the end of both processes, as activities for BIM and conventional processes are totally different.

Table 5.1: Time sheet for data collection

Time sheet for conventional process				
Project	Case study project 01			
Structure	Two-storey precast concrete housing project using load-bearing wall system			
Name and position				
Date	**No.**	**Product**	**Activity**	**Duration**
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			
YYYY.MM.DD	1			
	2			
	3			
	4			
	5			

5.4 Agility

Agility is the third attribute of the SCOR performance assessment. It is used to determine an ability of an organization to respond to positive and negative environmental influences. For agility, there are four major assessment components: upside flexibility, upside adaptability, downside adaptability, and value at risk. The value at risk can be eliminated directly because it does not have any direct relationship with BIM. Three remaining components can be further categorized based on major process of supply chain: source, make, deliver, source return, and deliver return. The assessment components are listed as follows.

i) Upside flexibility
- Upside source flexibility
- Upside make flexibility
- Upside deliver flexibility
- Upside source return flexibility
- Upside deliver return flexibility

ii) Upside adaptability
- Upside source adaptability
- Upside make adaptability
- Upside deliver adaptability
- Upside source return adaptability
- Upside deliver return adaptability

iii) Downside adaptability
- Downside source adaptability
- Downside make adaptability
- Downside return adaptability

The scope of BIM implementation extended from design and planning processes to an erection process. Design, planning, and production belong to a make process, while transportation and erection belong to a deliver process. Therefore, there are two supply chain processes selected for an assessment: make and deliver. Three remaining processes are unrelated and got excluded: source, source return, and deliver return. Therefore, there are five remaining components as follows.

- Upside make flexibility
- Upside deliver flexibility
- Upside make adaptability
- Upside deliver adaptability
- Downside make adaptability

Similar to reliability, an agility assessment encompassed a quantitative data collection. To determine improvements of each agility component, a new statistic must be recorded and benchmarked with old statistics. This assessment is inconsistent for the same reasons as reliability, such as the difference of precast concrete products, low quantity of production, and absence of recorded data.

The data collection for agility must be converted into qualitative data, which are collectable and more consistent. A data collection process was performed by using in-depth interview technique with experts of the case study company. The experts must evaluate existing performances of five assessment components, then re-evaluate BIM-based performances of the same components. The problems related to each component and achievable improvements were explored and clarified. After in-depth interviews, the data were summarized and concluded.

In conclusion, five components of agility were selected for a precast concrete supply chain performance assessment. The assessment was converted into a qualitative data assessment for consistency, which a data collection process can be performed by using an in-depth interview technique. The conventional problems associated with each component can be explored. Finally, improvements resulting from BIM can be addressed to benchmark supply chain performance improvements.

5.5 Cost

Cost is the fourth attribute of the SCOR performance assessment. It is used to determine costs required to operate processes in a supply chain. The SCOR provides a very comprehensive framework for a cost assessment, extended from source to return processes. This assessment is generally performed in a monthly basis to determine a financial condition of an organization. Based on the hypothesis, BIM tends to worsen cost performance of a supply chain, as BIM requires higher cost for adoption and implementation.

Similar to responsiveness, BIM does not affect every cost in a supply chain. BIM implementation affects directly only costs on design and planning processes, which belongs to a make process of a supply chain. Though BIM has potentials to reduce costs from better information management and collaboration, the cost driver for other processes depends on works in an operational level. For example, costs for production are based on productivity of labor, depreciation rate of equipment, labor skill, cost of equipment, and time required for production. Therefore, the cost associated with each activity of design and planning processes are selected to be assessed in details.

According to the SCOR standard, the cost for design and planning processes can be further categorized based on its source such as labor, automation, property, plant, overhead, and tax. Though there are various cost factors to be collected and benchmarked, some costs remain the same for both conventional and BIM-based processes. For example, a cost of plant and property is unaffected by an implementation of BIM. These unrelated costs were neglected for the assessment. There are two types of cost that are affected directly by the implementation of BIM: labor cost and automation cost.

The calculation of supply chain costs must be partially modified to fit this research project. As the assessments are performed based on the case study projects, a cost framework must be collected based on a project basis instead of a monthly basis. Also, an annual cost must be adjusted to an hour basis to calculate the unit cost with the collected process time.

The data for a supply chain cost assessment are separated into two types. The first type of data associated directly with an actual cost of the case study company, such as labor wage, and labor reward. These data are highly confidential and must be estimated based on relevant factors. For example, an estimation of labor wage is based on the position and experience of labors. An estimation must be based on costs of a market in the year this research was conducted. The second type of data is the non-cost data, such as depreciation rate, working policy, and working duration. These data can be collected directly during interviews.

However, for labor and automation costs, there were some costs got excluded from an assessment. For labor cost, costs for an overtime work must be excluded because the data were unavailable. Also, this cost must be assessed on a monthly basis. For automation, costs of electricity and network connection were neglected because they are insignificant. Table 5.2 shows an example calculation of supply chain costs. The unit for cost measurement is in Thai Baht (THB).

Table 5.2: Example of cost calculation

Case study project 01				
Conventional				
Activity	Unit cost (THB/hour)	Time		Total cost (THB)
		Hour	Minute	
Activity 01				
Labor cost	LC1	H1.1	M1.1	LC1 x (H1.1 + (M1.1 / 60)
Automation cost	AC1	H1.2	M1.2	AC1 x (H1.2 + (M1.2 / 60)
Activity 02				
Labor cost	LC2	H2.1	M2.1	LC2 x (H2.1 + (M2.1 / 60)
Automation cost	AC2	H2.2	M2.2	AC2 x (H2.2 + (M2.2 / 60)
Activity 03				
Labor cost	LC3	H3.1	M3.1	LC3 x (H3.1 + (M3.1 / 60)
Automation cost	AC3	H3.2	M3.2	AC3 x (H3.2 + (M3.2 / 60)
….	…	…	…	…

After data collection, the annual labor and automation costs obtained must be converted into a unit cost. Then, the total project cost can be calculated by using simple equations addressed in Table 5.2. The total supply chain costs of conventional and BIM-based processes can be benchmarked to determine percentage improvements. Also, labor cost and automation cost must be compared to determine an actual cost driver for BIM implementation.

In conclusion, supply chain cost can be assessed based on a cost framework provided from the SCOR model. The labor cost and automation cost associated with design and planning processes were selected for an assessment as they were affected directly from BIM. The data collection process can be performed using estimation and interview. Finally, cost improvements resulting from BIM can be addressed to benchmark supply chain performance improvements.

5.6 Asset management efficiency

Asset management efficiency is the last attribute of a SCOR performance assessment. The attribute is used to assess an overall supply chain efficiency of an organization comparing to values of its assets. In general, this assessment is performed in a yearly basis with three major components as follows.

- Cash-to-cash cycle time
  - Days sales outstanding
  - Inventory days of supply
  - Days payable outstanding
- Return on supply chain fixed assets
  - Supply chain revenue
  - Supply chain fixed assets
- Return on working capital
  - Accounts payable
  - Accounts receivable
  - Inventory

The calculation for each component requires annual statistical records of a case study company, for example, days sales outstanding can be calculated by dividing an annual average of gross accounts receivable by total gross annual sales. It is used to determine a duration between a purchase confirmation date and a cash received date. Days sales outstanding indicates an asset management performance of an organization.

Based on the hypothesis, BIM can indirectly improve overall processes in a supply chain from better management and collaboration. However, this assessment attribute is too broad to for the research project. Most of the assessment data focus on a whole business and are irrelevant to BIM. The annual basis of a data collection process is too long for two case study projects. Most importantly, the data for this attribute are generally the most confidential data for the case study company.

In conclusion, an asset management efficiency must be excluded from an assessment. The time frame is too broad for the case study project and the data are irrelevant to BIM.

5.7 Summary

A suitable supply chain performance assessment framework is required to assess supply chain improvements resulting from BIM implementation. Four SCOR assessment attributes were selected and modified according to fit characteristics of BIM and precast concrete supply chain. Reliability and agility data assessment were converted into a qualitative data assessment, which can be collected by using in-depth interview technique. Responsiveness and cost data were adjusted to fit BIM implementation on the case study projects. Both processes require specific databases before implementation to reflect actual practices of the case study company. Using four SCOR attributes, critical success factors of a supply chain (cost, time, and quality) can be assessed and benchmarked. Overall supply chain improvements resulting from BIM implementation can be determined.

CHAPTER VI
BIM IMPLEMENTATION

In this chapter, BIM implementation on the case study projects is presented with five major documentation outcomes. The conventional and BIM-based processes were performed, compared, and presented. This chapter consists of seven sections: BIM implementation (section 6.1), production drawing (section 6.2), assembly drawing (section 6.3), estimation sheet (section 6.4), reinforcement cut list (section 6.5), schedule (section 6.6), and summary (section 6.7).

6.1 BIM Implementation

After a BIM model development process for precast concrete structures was completed, BIM has been implemented in the case study company. Two precast housing projects were selected for an implementation. The first precast concrete house was a two-storey house using a load-bearing wall system. It has five types of precast concrete product with approximately 22 cubic meter of concrete volume. Table 6.1 lists the product quantity of the cast study project 01.

Table 6.1: Product list of case study project 01

No.	Product	Quantity
1	Footing	0
2	Ground beam / Beam	27
3	Column	15
4	Tray	4
5	Wall	22
6	Stair	1
7	Slab	0
	Total	69
	Total concrete volume (m^3)	21.95

The second case study was a two-storey house using a skeleton-frame system. It has seven types of precast concrete products with approximately 22.5 cubic meter of concrete volume. Table 6.2 lists the products of the cast study project 02.

Table 6.2: Product list of case study project 02

No.	Product	Quantity
1	Footing	11
2	Ground beam / Beam	49
3	Column	16
4	Tray	3
5	Wall	2
6	Stair	5
7	Slab	69
	Total	155
	Total concrete volume (m^3)	22.45

These case study projects have similarities in a product design. Though the product quantity of the second case study project were twice of the first case study project, the total volume of concrete for these two case study projects were close. Both projects had a major difference in a structural system, which was directly related to the complexity of a design process.

Using Autodesk Revit, the BIM models for both case study projects were developed. The prepared BIM model development process was used for a model creation. Figure 6.1 illustrates a three-dimensional image of a BIM model of a case study project 01 developed in Autodesk Revit.

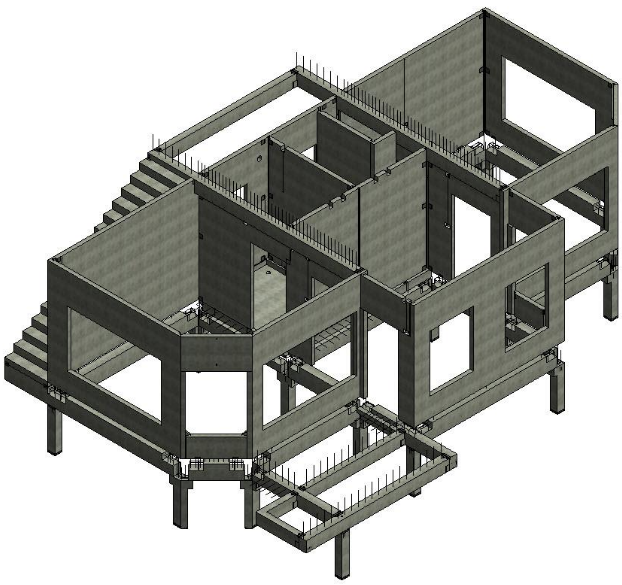

Figure 6.1: A Three-dimensional model of the case study project 01

After the BIM model for the case study project 01 was completed, the data were collected based on the modified SCOR assessment framework. Then, the second BIM model for the case study project 02 was developed. Figure 6.2 illustrates a three-dimensional image of a BIM model of a case study project 02.

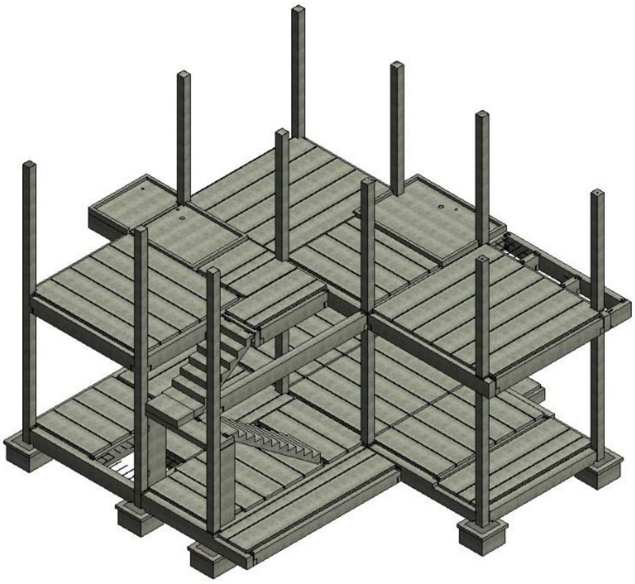

Figure 6.2: A Three-dimensional model of the case study project 02

Using the developed BIM models, the major documentation outcomes from design and planning processes were generated and converted into paper-based documents. There were five major outcomes published for comparisons: production drawing, assembly drawing, estimation sheet, reinforcement cut list, and schedule. Each BIM-based outcome was compared with the conventional outcome to determine improvements and limitations. Based on the hypothesis, BIM should improve overall quality and timeliness of these documentation processes.

It must be noted that conventional labors for the case study project 01 and 02 were similar for consistency in a benchmarking process. Also, the figures presented in this chapter were partially modified to protect confidential information of the case study company.

6.2 Production Drawing

Production drawings are the first outcome of design and planning processes. Using the prepared database, the components of production drawing such as product images, specifications, symbols, and annotations, were created without difficulties. However, as most products of the case study projects were engineered-to-order products, the model creation process required time for the development. Production drawings were prepared and published after the BIM model was completed. Figure 6.3 illustrates examples of production drawings of precast concrete beam and precast concrete column respectively.

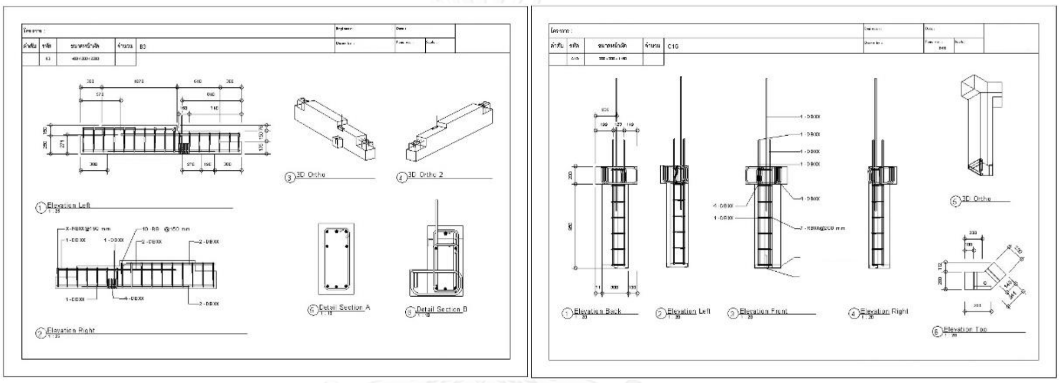

Figure 6.3: Production drawings

An accuracy of a production drawing is directly related to quality of production. Ideally, production drawings should be published with a perfect accuracy. A common mistake in a production drawing, such as an incorrect dimension, can led to a troublesome correction process in production. In general, production drawings are developed by using a two-dimensional design tool, which requires high expertise of the engineer and draftsman to design products individually. Also, a revision process must be performed manually, which is ineffective and time consuming. It was found that the conventional process for creating production drawings is fallible and requires a suitable design tool.

Using a BIM tool, the design process can be simplified. The three-dimensional ability of a BIM tool can improve collaboration between an engineer and draftsman significantly. Some general tasks, such as a sectional drawing creation process, became redundancy works. Changes can be applied with ease because specifications and dimensions were directly connected to the drawings. It resulted in a significant reduction of human errors. Also, the process time requires for BIM is slightly shorter. However, as production drawings require a very comprehensive product database, BIM implementation requires time for adoption. Also, an expertise of a BIM modeler is required for the documentation process.

Compared the final production drawings obtained from BIM to conventional processes, the drawings obtained from BIM is more accurate with higher flexibility. The working process became systematic using an automation provided from a BIM tool. The collaboration between an engineer and draftsman was improved greatly. Overall, BIM showed a good potential to improve processes and outcomes for the production drawing.

6.3 Assembly Drawing

Assembly drawings are the second most important documentation outcomes from design and planning processes. After precast concrete products were modeled, they were transferred into a project and assembled to form a structure. Assembly drawings were created, published, and compared. Figure 6.4 illustrates an example of precast concrete assembly drawing of precast concrete columns.

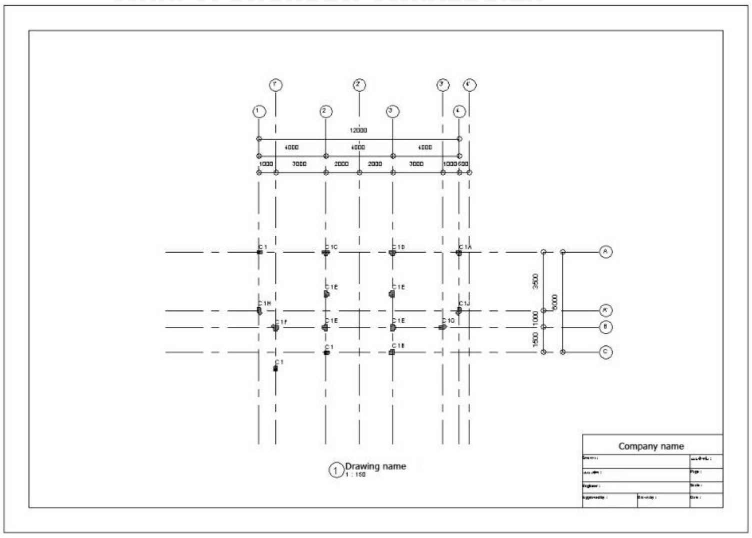

Figure 6.4: Assembly drawing

For a conventional process, assembly drawings are created by using a two-dimensional design tool. The task is usually performed in parallel with production drawings to determine proper dimensions of each precast concrete product. This process of collaboration between drawings requires high expertise of draftsman and engineer. Mistakes in assembly drawings also led to mistakes in production drawing. Due to these difficulties, this process is ineffective and fallible. Furthermore, the revision process must be performed manually by using a visual inspection. It is unsystematic and can led to various losses in a supply chain.

Using BIM, both production drawing and assembly drawing can be fully synchronized. The information from production drawings consist of a three-dimensional characteristic, which can be assembled directly to form an assembly model in assembly drawings. It can directly eliminates the redundancies and hastens the process significantly. Figure 6.5 illustrates an example of a three-dimensional image of disassembly products of the case study project 01.

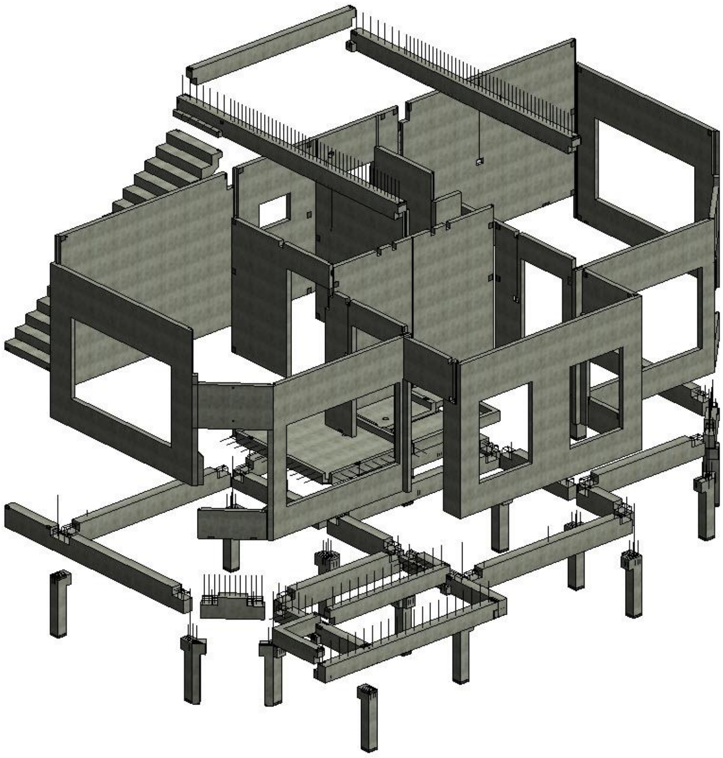

Figure 6.5: Three-dimensional assembly drawing

Using three dimensional coordination ability of a BIM tool, clashes between assembled concrete products can be inspected and determined automatically. Figure 6.6 illustrates a clash detection function of a BIM tool. The clash between two precast concrete walls was determined and highlighted for a correction.

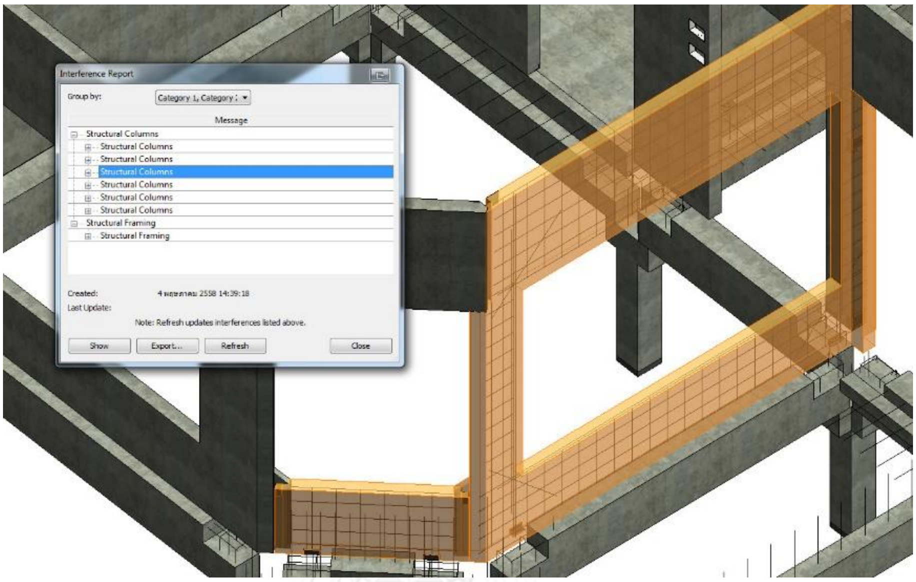

Figure 6.6: Clash detection function of a BIM tool

Changes are another important issue that need to be focused for assembly drawings. When a single precast concrete product is subjected to change, for example, an elevation of a precast concrete slab is modified, other products associated with a changing product must be revised for change too. The three-dimensional coordination ability of a BIM tool enable users to inspect interferences between products in a new position, which is a systematic way to deal with changes and interferences. However, misalignments of embedded parts must be revised manually by using a visual inspection, as there is no interference for this type of mistake.

Compared assembly drawings of BIM and conventional processes, BIM outcomes show higher potential with accuracy and flexibility. The working process was faster with better collaboration between working units. It was found that the three-dimensional coordination and clash detection abilities of a BIM tool can solve most problematic issues for this document.

6.4 Estimation Sheet

Estimation sheets are the third outcome from design and planning processes. Using the prepared template, the estimation sheets were generated automatically after a BIM model completion. There were three types of quantification prepared in the design template: product list, material estimation sheet, cost estimation sheet.

In general, estimation sheets are created manually without a specific computation tool. An engineering unit or production unit is responsible for the calculation. For made-to-stock products and made-to-order products, the calculation is simple. It requires only a standard for calculation, such as a unit quantity for a particular product and a unit cost per area. In contrary, for an engineered-to-order products, there are difficulties in a manual calculation process, which requires time and effort from the responsible unit. Though mistakes from this document do not affect considerably on critical success factors, a conventional process still requires time for manual calculation and revision.

Quantification (or) quantity takeoff is one of the most useful benefits of BIM. After developing a comprehensive database, all quantification processes can be fully automated with exact outcomes in different metrics such as concrete in volume, embedded part in piece, and reinforcement bars in total weight. A product list can be generated with specific details accordingly, for example, a precast beam list can be generated with ID, type, shape, corbel quantity, dimensions, concrete volume, and product weight. The equations required for computation can be prepared with high flexibility. Table 6.3 demonstrates an example of a precast beam quantification sheet generated from a BIM model. The list was arranged by an elevation level and product ID.

For cost estimation sheets, they were prepared according to the cost metrics of different products. For example, precast concrete slabs require total area of slabs for cost calculation. The area parameter of each slab can be included, calculated, and summed in a slab database for an automated estimation. Material costs for a project can also be determined by sorting cost information according to each materials.

Table 6.3: Precast concrete beam quantification sheet

ID	Type	No. of corbels	*Dimensions*					Concrete volume	Weight (kg.)
			Width	Depth	Length 1	Length 2	Total		
Level 1									
B1	3-3	0	0.20	0.33	2.28	-	2.28	0.13	312.48
B1A	3-3	0	0.20	0.40	1.78	-	1.78	0.12	298.56
B1B	3-3	0	0.20	0.40	1.78	-	1.78	0.12	298.56
B1CL	3-3	0	0.20	0.40	2.78	-	2.78	0.20	490.56
B1E	3-3	0	0.20	0.40	1.28	-	1.28	0.08	202.56
B1X	3-3	2	0.20	0.40	2.49	-	2.49	0.17	402.48
B2	3-3	0	0.20	0.40	3.78	-	3.78	0.28	682.56
B2A	3-3	0	0.20	0.40	3.78	-	3.78	0.28	682.56
B2B	3-3	0	0.20	0.40	3.78	-	3.78	0.28	682.56
B3	3-3	1	0.20	0.40	2.28	-	2.28	0.15	367.20
B3A	3-3	0	0.20	0.40	3.28	-	3.28	0.24	586.56
B3X	3-0	0	0.20	0.40	4.69	-	4.69	0.37	878.88
B5	3-3	1	0.20	0.33	3.78	-	3.78	0.23	551.88
B6	3-3	2	0.20	0.33	3.78	-	3.78	0.23	557.28
BS1	2-2	0	0.20	0.33	1.38	-	1.38	0.06	150.66
BS1B	2-2	0	0.20	0.30	2.78	-	2.78	0.12	289.44
BS1X	2-0	1	0.15	0.30	3.99	-	3.99	0.24	572.76
BS2	2-2	1	0.15	0.33	1.80	-	1.80	0.09	205.20
BS3	3-0	2	0.20	0.30	2.28	-	2.28	0.13	317.52
BS4	2-2	1	0.15	0.33	2.28	-	2.28	0.11	261.36
B1CR	3-3	0	0.20	0.40	2.78	-	2.78	0.20	490.56
B1D	3-3	0	0.20	0.40	1.11	-	1.11	0.07	169.92
B1D	3-3	0	0.20	0.40	1.11	-	1.11	0.07	169.92
BS1A	2-2	0	0.15	0.30	1.19	0.99	2.18	0.09	208.44
								4.10	
Level 2									
BS9X	2-0	1	0.20	0.33	5.79	-	5.79	0.38	901.44
BS9Y	2-0	1	0.20	0.33	5.79	-	5.79	0.38	901.44
BS1Y	2-2	0	0.15	0.33	3.78	-	3.78	0.18	431.46
								0.93	
27						Total concrete volume		**5.03**	

For reinforcement steel bars, quantification sheets can be sorted by type, size, and shape of reinforcement steel bars. Table 6.4 demonstrates an example of reinforcement quantification sheet generated from a BIM model.

Compared BIM to conventional processes, a BIM-based quantification process was definitely superior. With a proper database, BIM quantification can be fully automated with very high accuracy. The collaboration between engineering unit and production unit can be improved. As BIM information are centralized, quantification sheets are adjusted to changes automatically. Furthermore, human errors can also be eliminated from the automated calculation.

Table 6.4: Reinforcement quantification sheet

Shape	Length	Quantity	Total length	@ distance	Number of
Cauldron 4 mm.					
Straight	0.16	-	2.40	20	2
U-Shape	0.21	4	0.84	20	1
U-Shape	0.34	-	12.24	-	4
U-Shape	0.35	-	5.95	20	2
U-Shape	0.36	-	6.12	20	2
	Total cauldron 4 mm. length		**27.55**		
Cauldron 6 mm.					
Straight	0.19	15	2.85	15	1
Straight	0.20	15	3.00	15	1
Straight	0.22	-	3.96	-	2
Straight	0.23	12	5.52	15	2
Straight	0.24	11	2.64	15	1
Straight	0.28	-	3.92	-	2
Straight	0.29	-	4.35	15	1
Straight	0.37	11	9.99	-	2
Straight	0.38	18	8.36	15	2
Straight	0.39	27	8.97	15	2
Straight	0.40	-	9.20	15	2
Straight	0.43	-	4.73	15	3
Straight	0.46	6	8.28	15	1
Straight	0.47	15	12.69	10	1
Straight	0.48	15	21.12	15	1
Straight	0.49	9	28.42	-	4
Straight	0.54	-	3.24	15	6
Straight	0.64	-	9.60	15	1
…	…	…	…	…	…

By using BIM, overall flexibility of this documentation process was improved from centralized information management. BIM improved timeliness and quality for this outcome. The working process became systematic and fast. Though estimation sheets are not vital for precast concrete tasks, BIM shows great potential to generate this outcome from full automation.

6.5 Reinforcement Cut List

Reinforcement cut lists are also generated from BIM after a model completion. For a conventional process, this list is generally created manually without a specific computation tool, similar to an estimation sheet. The process is fallible, as an error in this list directly affects raw material consumption in a production process. This documentation also requires high expertise for accuracy, especially for engineered-to-order products. The revision process is also unsystematic and troublesome.

To create reinforcement cut lists using a BIM tool was not a simple task. As a BIM tool was not design directly for a production purpose, the automated function for cut list creation was absent. The template and database were prepared specifically to input required parameters for a cut list creation. For example, a text parameter must be assigned to every reinforcement steel bar to identify its product host. Table 6.5 demonstrates an example of a reinforcement cut list of five precast concrete beams in texts.

Table 6.5: Reinforcement cut list of precast beams

Type	Shape	Length (m.)	Quantity	Total length	@ distance	Number of group	Dimensions (m.)			
							A	B	C	D
Beam : B1										
DB1X	L-Shape	0.75	1	0.75	-	2	0.00	0.00	0.00	0.00
DB1X	Straight	0.76	1	0.76	-	1	0.00	0.76	0.00	0.00
DB1X	Straight	2.23	2	4.46	-	2	0.00	2.23	0.00	0.00
RBX	Stirrups	0.89	13	11.57	20	1	0.04	0.28	0.15	0.25
Beam : B1A										
DB1X	Straight	0.59	1	0.59	-	1	0.00	0.59	0.00	0.00
DB1X	L-Shape	0.72	1	0.72	-	1	0.00	0.33	0.43	0.00
DB1X	L-Shape	0.73	1	0.73	-	1	0.00	0.28	0.49	0.00
DB1X	Straight	1.73	2	3.46	-	2	0.00	1.73	0.00	0.00
RBX	Stirrups	1.04	10	10.40	20	1	0.04	0.35	0.15	0.35
Beam : B1B										
DB1X	Straight	0.59	1	0.59	-	1	0.00	0.59	0.00	0.00
DB1X	L-Shape	0.73	1	0.73	-	1	0.00	0.43	0.34	0.00
DB1X	L-Shape	0.75	1	0.75	-	1	0.00	0.51	0.28	0.00
DB1X	Straight	1.73	2	3.46	-	2	0.00	1.73	0.00	0.00
RBX	Stirrups	1.04	10	10.40	20	1	0.04	0.35	0.15	0.35
Beam : B1CL										
DB1X	L-Shape	0.73	1	0.73	-	1	0.00	0.28	0.49	0.00
DB1X	L-Shape	0.74	1	0.74	-	1	0.00	0.49	0.28	0.00
DB1X	Straight	0.93	1	0.93	-	1	0.00	0.93	0.00	0.00
DB1X	Straight	2.73	2	5.46	-	2	0.00	2.73	0.00	0.00
DB1X	Straight	0.93	1	0.93	-	1	0.00	0.93	0.00	0.00
DB1X	Straight	2.73	2	5.46	-	2	0.00	2.73	0.00	0.00
RBX	Stirrups	1.04	15	15.60	20	1	0.04	0.35	0.15	0.35
Beam : B1CR										
DB1X	Straight	0.90	1	0.90	-	2	0.00	0.90	0.00	0.00
DB1X	Straight	2.72	2	5.44	-	1	0.00	2.72	0.00	0.00
DB1X	Straight	2.73	2	5.46	-	1	0.00	2.73	0.00	0.00
RBX	Stirrups	1.04	15	15.60	20	1	0.04	0.35	0.15	0.35

However, a BIM tool was still unable to achieve to all requirements for creating a reinforcement cut list. For example, the tool was unable to generate three-dimensional reinforcement steel bars. A sheet creation process was time consuming, especially for a customized production of the case study company. Overall, a manual process and expertise were required for this type of documentation. It must also be noted that some add-ons for a BIM tool can be used to serve this task. The SOFiSTiK Reinforcement Detailing from SOFiSTiK AG has a good potential to generate and manage outcomes for this document.

Compared BIM and conventional processes, BIM requires less manual effort and provides higher accuracy. The information in a reinforcement cut list can be connected to a BIM model and centralized for flexibility. Though BIM provides partial automation for reinforcement cut lists, the documentation still requires high expertise and time. A suitable BIM tool was still required for an advancement in the automation.

6.6 Schedule

Schedules are the final outcome from design and planning processes. Based on the prepared database, three types of schedule were prepared and generated from a BIM model: production schedule, transportation schedule, and erection schedule. The checklists were also generated for different monitoring tasks.

In general, schedules are prepared after production drawings receive an approval. A scheduling process starts backward, from erection schedule, transportation schedule, and production schedule respectively. A project management tool is used to crate graphical outputs for management, such as Gantt chart, and s-curve. These information can also connect to checklists for a progress monitoring process. The conventional process for schedule preparation is not complex or time consuming, but it still can be further improved for better management.

Using BIM, time parameters for scheduling can be assigned to each precast product in a BIM model. The schedule can be generated using a simple equation and provides similar results obtained from a conventional process. Using centralized information, BIM can connect product information to different schedules. If change occurs, BIM-based schedule is updated automatically. Figure 6.6 demonstrates an example of a production schedule generated automatically from a BIM tool.

Table 6.6: Production schedule

Product	Product ID	Production Sequence	Production schedule		Production status		
			Plan	Actual	Preparation	Casting	Approval
Level 01							
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1A	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1B	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1C	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1D	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1F	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1G	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1H	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1I	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1J	2	2015.MM.DD	2015.MM.DD	✓	✓	
Beam	B1	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1A	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1B	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1CL	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1E	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1X	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B2	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2A	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2B	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3A	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3X	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B5	5	2015.MM.DD	2015.MM.DD	✓		
…	…	…	…	…	…	…	…

Furthermore, a checklist for each process can be assigned to a product information with schedule for management. For example, a production checklist, which includes parameters for reinforcement preparation, embedded parts preparation, mold assembly, approval, etc., can be arranged with a schedule to connect a progress with time. The scheduling and monitoring processes in production, transportation, and erection can be benefited from BIM. The collaboration between production unit, quality control unit, transportation unit, and erection unit also simplified and improved. Table 6.7 demonstrates an example of checklist generated from a BIM tool.

Compared BIM and conventional processes, BIM is slightly superior to a conventional process. The collaboration with BIM is more effective as BIM can connect production drawings and assembly drawings with the schedules. Changes in design can be managed with ease using automation. With good preparation, the graphical information can be generated as an output from a BIM tool, such as S-curve. Furthermore, the centralized information can collaborate all responsible units for production, transportation, and erection processes. It results in an improvement in management. In conclusion, though outcomes from a conventional process was efficient to a certain level, BIM can provide superior outcomes for overall management in a supply chain.

Table 6.7: Production checklist

Product	Product ID	Production Sequence	Production checklist								
			Cleaning	Mold assembly	Reinforcement placement	Embedded part placement	1st inspection	Concrete casting	Surface finishing	Mold removal	2nd inspection
Column	C1	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1A	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1B	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1C	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1D	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1E	1	✓	✓	✓	✓	✓	✓	✓	✓	✓
Column	C1E	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1E	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1E	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1F	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1G	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1H	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1I	2	✓	✓	✓	✓	✓	✓	✓		
Column	C1J	2	✓	✓	✓	✓	✓	✓	✓		
Beam	B1	3	✓	✓	✓	✓					
Beam	B1A	3	✓	✓	✓	✓					
Beam	B1B	3	✓	✓	✓	✓					
Beam	B1CL	3	✓	✓	✓	✓					
Beam	B1E	3	✓	✓	✓	✓					
Beam	B1X	3	✓	✓	✓	✓					
Beam	B2	4	✓	✓	✓	✓					
Beam	B2A	4	✓	✓	✓	✓					
Beam	B2B	4	✓	✓	✓	✓					
Beam	B3	4	✓	✓	✓	✓					
Beam	B3A	4	✓	✓	✓	✓					
Beam	B3X	4	✓	✓	✓	✓					
Beam	B5	5	✓	✓	✓	✓					
…	…	…	…	…	…	…	…	…	…	…	…

6.7 Summary

In this chapter, BIM implementation on two precast concrete projects were explained. The major outcomes from design and planning processes were generated, compared, and analyzed.

For production drawings and assembly drawings, the outcomes were superior from the direct benefits of a BIM tool. It was found that three-dimensional interference detection function of a BIM tool is the key to solve most of problematic issues for drawing creations. The estimation sheets can be fully automated with high flexibility and accuracy. All estimation tasks were eliminated directly from an automated quantification function of a BIM tool. For reinforcement cut list, BIM provides better outcomes with higher accuracy. However, a BIM tool still requires suitable functions for this task. And for schedules, the outcomes can be slightly improved by using centralized information management.

In conclusion, BIM shows very good potential to improve flexibility, accuracy, and timeliness for documentation processes. Three major documentation outcomes (production drawing, assembly drawing, and estimation sheet) can gain most benefits directly from BIM, whereas two remaining documentation outcomes (reinforcement cut list and schedule) can be improved slightly. These improvements in documentation must be one of the major concerns of BIM adoption for precast concrete contractors.

CHAPTER VII
RESULTS AND DISCUSSIONS

This chapter presents the comparative results of supply chain attributes, which are based on the modified SCOR assessment framework. It has a major purpose to explain achievable precast concrete supply chain improvements resulting from BIM implementation. The problematic issues related to each assessment attribute are clarified with BIM solutions. The chapter consists of five sections: reliability (section 7.1), responsiveness (section 7.2), agility (section 7.3), cost (section 7.4), and summary (section 7.5).

After BIM models were completed, five major documentation outcomes obtained from conventional and BIM-based processes were compared and analyzed. Then, the results were summarized and presented to three experts of the case study company. BIM potentials for each precast concrete tasks were explained with examples. Then, the interviews were conducted for data collection.

After a data collection process, the data for four attributes were analyzed and benchmarked. The calculation for quantitative results of cost and time were performed to determine overall percentage improvements. Finally, the supply chain performance improvements were concluded as the results.

7.1 Reliability

For reliability, there were four components used for the assessment: perfect quantity, perfect delivery, perfect documentation, and perfect condition. Examples of problems for each component were explained with possible solutions from BIM.

7.1.1 Perfect quantity

Perfect quantity is the first component for a reliability assessment. As precast concrete encompasses a discrete manufacturing, the assessment was modified accordingly. Comparing a precast concrete industry to other manufacturing industries, the quantity of production is comparatively low. Each precast product must get an approval by a quality control unit before the delivery. The common perfect quantity assessment, which consider large quantity of production is too broad for this precast concrete characteristic. This research focused further in details to the material quantity of a supply chain for an assessment. Examples of problems that affect perfect quantity are listed as follows.

- The product must be repaired or reproduced due to mistakes in a production process, such as wrong positioning of embedded parts, wrong dimensions from mold preparation.
- An excessive production caused from mistakes in collaboration between different units.
- The production is delayed due to shortage of a specific raw material such as steel plate of specific dimensions, and PVC pipe of a specific length.

For perfect quantity, mistakes which resulted in an excessive material consumption are directly affect cost of a make process, while the shortage of material directly affect duration of a make process. By implementing BIM, perfect quantity can be improved as follows.

- The implementation of BIM can effectively reduce mistakes in design and planning processes, which are generally led to mistakes in production and affect a material quantity.
- Three-dimensional visualization ability of a BIM tool can simplify material preparation for production. It also reduce human errors in make process, especially for complex engineered-to-order products.
- Mistakes resulting from poor collaboration in a supply chain can be reduced by using centralized information from a BIM tool.
- Automated quantification ability can simplify source process for a specific material. The manual process is also fallible for large amount of documents. These manual errors can be directly reduced by using automation.

Therefore, as BIM has a good potential to improve outcomes from design and planning processes, it can directly improve perfect quantity component. In specific, BIM can benefits more for the complex production of engineered-to-order products.

7.1.2 Perfect delivery

Perfect delivery is the second component for reliability. For a precast concrete supply chain, delivery process deals with both transportation and erection. The assessment for delivery component must consider tasks on the operational level. Examples of problems that affect perfect delivery are listed as follows.

- Ineffective scheduling and monitoring cause delays in a deliver process. Delivery planning is troublesome because deliver flows always varies with flows in make process. The schedules require an update on a daily basis.
- The product loading process is delayed due to the lack of a proper inventory management. It is also resulted from poor collaboration between production unit and transportation unit.
- A product ID is commonly written on a product by production workers. This manual coding system is fallible, especially for similar products with a different production date. It results in mistakes in product loading for transportation.
- Errors in an erection process caused from inaccurate documents. It is generally related to an accuracy of documents from design and planning processes.

BIM can affect a delivery process indirectly from better collaboration and management. Flows of information can be managed systematically to support each unit on the operational level. The implementation of BIM can improve perfect delivery as follows.

- As progress monitoring must be performed on a daily basis, transportation and erection schedules are subjected to change regularly. These changes can be managed with ease using centralized information management and automation of BIM. It simplifies scheduling process and can directly improves perfect delivery.
- BIM can improve collaboration between production unit, transportation unit, and erection unit effectively.
- BIM can be utilized for an inventory management to improve perfect delivery. By creating grid lines in a storage area, the location of each product can be identified and stored in a BIM model for an inventory management.

- Minor problems, such as errors from handwriting, can be eliminated by working on digital-based documents.
- Using a three-dimensional model, the complex part of an erected structure can be clarified with ease. BIM can reduce errors in erection process. Perfect delivery can be directly improved.

Although perfect delivery is directly related to tasks on the operational level, BIM has some potential to improve this component indirectly from better management. As there are multiple working units responsible for a delivery process, perfect delivery requires good collaboration. Centralized information in a BIM model can improve the collaboration. The scheduling and monitoring processes can also be improved from an automation. However, the automation for a delivery management required a comprehensive database specifically prepared for the tasks.

7.1.3 Perfect documentation

Perfect documentation is the third component for reliability. The component is used to indicate accuracy and timeliness of documents submitted to customers on delivery. Most of documents associated with BIM are related to technical documents such as production drawing, assembly drawing, and quantification sheet, which are the documentation outcomes obtained from the design BIM model. Using a conventional process, examples of problems related to perfect documentation are listed as follows.

- As most documents must be performed manually, most of the mistakes are caused from human errors. These errors are also depended on various factors, such as design complexity, lack of expertise, inefficient duration, and lack of appropriate design tools.
- Changes occur in design and planning processes must be applied to all relevant documents, for example, a change in a production drawing affects other production drawings, assembly drawings, and estimation sheets. This change revision is also time consuming and fallible from a manual process.
- Using an ineffective tool results in working redundancies. It worsens timeliness of a documentation process.

- Documentation processes require good collaboration between different working units, such as design unit, production unit, transportation unit, and erection unit. With ineffective information management, a conventional process causes documentation errors and delays.

For perfect documentation, BIM can improve this component directly, as it improve information management of a supply chain. BIM potentials to improve perfect documentation are listed as follows.

- Using an interference detection ability of a BIM tool, mistakes from the design complexity can be minimized. It can directly improves an accuracy of the outcomes for documentation.
- Some mistakes caused from human errors can be eliminated directly from an automation. Also, mistakes caused from inefficient accuracy can be eliminated in the same way.
- Redundancies can also be eliminated using various function of a BIM tool, such as a sectional drawing creation process, quantification process, and revision process. The timeliness of perfect documentation can be improved.

BIM implementation has a direct effect on perfect documentation, which can improve this assessment component significantly. The documentation process can be performed systematically with higher accuracy and timeliness. For reliability, perfect documentation can gain most benefits from BIM implementation.

7.1.4 Perfect condition

Perfect condition is the last assessment component for reliability. The component deals with the condition of a product delivered to the customer. The product condition must meet specifications and properly accepted by the customer to achieve criteria of the component. Based on the assessment conditions, perfect condition almost has no direct relationship with BIM. However, there are some problematic issues which can be managed and improved by using BIM. Examples of problems related to perfect condition are listed as follows.

- The surface of a precast concrete product cracked after an erection process due to mistakes in placements of embedded parts.
- Mistakes from design and production processes, such as wrong number in production drawings and wrong dimensions of products, require corrections in an erection process. It results in product damages and worsens the component.

Similar to perfect delivery, BIM can indirectly improve this component from better management and collaboration. BIM can improve perfect condition as follows.

- The product details can be clarified and simplified using a three-dimensional visualization ability of a BIM tool. It can reduce mistakes from confusions in a design and improve a product condition when delivered.
- The collaboration between design unit, production unit, transportation unit, and erection unit can be improved from a systematic information management. It can result in error reduction and improve the component.

BIM can indirectly improve this component as it provides better documentation outcomes for design and planning processes. The collaboration between responsible units can be improved and affect perfect condition. However, the major criteria required to improve perfect condition depends on processes on the operational level. BIM has least potential to improve this component.

It must be noted that the reliability results also depends on opinions of the interviewees towards BIM which may cause bias in the qualitative outcomes.

7.2 Responsiveness

Responsiveness is the second SCOR attribute used to assess time performance of a supply chain. During BIM implementation, time sheets were used to record durations of each activity for both conventional and BIM-based processes. Between these two processes, the durations were also recorded separately based on design and planning activities. This assessment was performed on a project level, which data were collected for two case study projects. After the BIM model of the case study project 01 was completed, the times were summarized. Table 7.1 illustrates the process time of the case study project 01.

Table 7.1: Process time of case study project 01

Conventional process		
Activity	Duration	
	Hour	Minute
1 Production drawing creation		
Beam / Ground beam	19	30
Column	19	0
Tray	3	30
Wall	44	15
Stair	3	45
Total	90	0
2 Assembly drawing creation		
Plan view	7	30
Elevation view	8	20
Total	15	50
3 Quantification		
Estimation sheet	7	50
Reinforcement cut list	13	40
Total	21	30
Total time of conventional process	**127**	**20**

BIM-Based process		
Activity	Duration	
	Hour	Minute
1 Product model creation		
Beam / Ground beam	5	45
Column	2	30
Tray	0	50
Wall	8	30
Stair	0	50
Total	18	25
2 Assembly model creation		
Basic components	0	20
Product assembly	3	30
Total	3	50
3 Reinforcement creation		
Beam / Ground beam	8	10
Column	4	10
Tray	1	30
Wall	14	25
Stair	1	15
Total	29	30
4 Drawing creation		
Product assembly creation	8	35
Sheet creation	17	40
Total	26	15
5 Documentation		
Estimation sheet	2	15
Total	2	15
Total time of BIM-based process	**80**	**15**

The second BIM model for the case study project 02 was developed after the first case study project was completed. Table 7.2 illustrates the process time of the case study project 02.

Table 7.2: Process time of case study project 02

Conventional process		
Activity	Duration	
	Hour	Minute
1 Production drawing creation		
Footing	2	0
Beam / Ground beam	35	15
Column	17	15
Tray	4	45
Wall	1	15
Stair	11	0
Slab	4	0
Total	75	30
2 Assembly drawing creation		
Plan view	9	45
Elevation view	11	30
Total	21	15
3 Quantification		
Estimation sheet	10	15
Reinforcement cut list	18	20
Total	28	35
Total time of conventional process	**125**	**20**

BIM-Based process		
Activity	Duration	
	Hour	Minute
1 Product model creation		
Footing	0	30
Beam / Ground beam	11	15
Column	3	0
Tray	0	40
Wall	0	15
Stair	2	10
Slab	1	30
Total	19	20
2 Assembly model creation		
Basic components	0	15
Product assembly	4	30
Total	4	45
3 Reinforcement creation		
Footing	0	30
Beam / Ground beam	10	30
Column	3	10
Tray	1	20
Wall	0	15
Stair	2	30
Slab	0	30
Total	18	45
4 Drawing creation		
Product assembly creation	9	20
Sheet creation	19	25
Total	28	45
5 Documentation		
Estimation sheet	1	45
Total	1	45
Total time of BIM-based process	**73**	**20**

Compared BIM to conventional process times, BIM required longer duration to develop a three-dimensional model, especially for the reinforcement steel bars. However, after a BIM model was completed, it can be automated for various tasks, such as a sectional drawing creation, three-dimensional model creation, and quantification. The process times required for these activities were minimized directly from an automation.

In general, a total quantity of product should directly affect design and planning times in a supply chain. The process times should be increased with large quantity of products. It is not a proper statement for a supply chain of the case study company. Considering the total quantity of precast concrete products, the case study project 02 has approximately twice of the product quantity compared to the case study project 01. However, the process time for both projects were very close due to the difference in product complexity. The case study project 02 has 70 pieces of precast concrete footing and precast concrete slab, which are made-to-stock products. These products require minimum time for a design process, as they have a fixed standard of production. It was found that the complexity of design is the most influential factor that affect process time for BIM implementation.

Table 7.3 compares percentage improvement of process times between case study project 01 and 02.

Table 7.3: Percentage improvement of process time

Results				
Case study project 01				
Conventional process	127	Hours	20	Minutes
BIM-based process	80	Hours	15	Minutes
Percentage improvement	36.98			
Case study project 02				
Conventional process	125	Hours	20	Minutes
BIM-based process	73	Hours	20	Minutes
Percentage improvement	41.49			

Using BIM, overall process times were reduced significantly at 36.98% and 41.49% for the case study project 01 and 02 respectively. However, these improvements of process times also depend on various factors, such as an expertise of BIM modeler, complexity of a project, and performance of existing conventional process. In conclusion, BIM showed a great potential to improve process time for design and planning processes in a precast concrete supply chain.

7.3 Agility

Agility assessment for this research project was prepared based on the scope of BIM implementation, which five agility components were selected for the assessment: upside make flexibility, upside deliver flexibility, upside make adaptability, downside make adaptability, and upside deliver adaptability.

7.3.1 Upside make flexibility

Upside make flexibility is used to determine a potential of a precast company to design and produce unplanned products for additional quantity of 20% without a material constraint. For example, if a precast concrete company can design and produce approximately 100 pieces of product per month, how long it would take to design and produce additional 20 products unexpectedly. The quantity of unexpected product increment can be adjusted accordingly to different companies.

To improve precast concrete upside make flexibility, it is obvious that the duration of a make process must be shortened with higher productivity and flexibility. Considering a precast concrete supply chain, product design is the major time consuming process in a process make. In general, the time required to design a single precast concrete housing project is approximately three weeks, whereas the time required for production is approximately a week. Using BIM, time required for design and planning processes can be reduced significantly, which upside make flexibility can get a direct improvement for the timeliness.

It must be noted that the amount of design tasks is generally less than production tasks for a mass production of precast concrete products. Therefore, the time required for product design may not always be the most critical time. However, for the case study company, it focuses on a unique single precast concrete housing project. The ration between design and production is high, which results in more achievable improvements for this component.

Unexpected changes always result in a troublesome correction process. Using a BIM tool, these correction tasks can be simplified. The centralized information can automatically update changes into a BIM model, which connected to other documents, such as assembly drawing, and estimation sheet. Therefore, BIM has a good potential improve flexibility for change significantly. However, a faster design process would not be benefited if it exceed the maximum production capacity.

In conclusion, BIM has a great potential to improve upside make flexibility. The implementation of BIM can also support production process in make indirectly by reduce errors, simplify product drawing, and improve collaboration.

7.3.2 Upside deliver flexibility

Upside deliver flexibility is used to determine the potential of a precast concrete company to transport and erect unexpected products for an additional quantity of 20%. The assessment did not consider a finished product constraint. For example, if a precast company can transport and erect approximately 100 pieces of product per month, how long it would take to transport and erect additional 20 products unexpectedly.

In general, compared to a make process, the characteristics of a delivery process are greatly different. The capacity of transportation and erection process can be increased by outsourcing delivery tasks to other companies, for example, products can be transported by using service trucks. Hence, the maximum capacity for delivery process depends on the company resource and the availability of outsourced units. For the case study company, outsourced units can be procured for both transportation and erection processes.

Using BIM, scheduling and monitoring process can be managed faster with less errors. The collaboration between transportation unit and erection unit can be performed using a BIM tool. The erection process can be managed with ease with three-dimensional visualization ability of a BIM tool. These benefits of BIM can improve overall management of a deliver process, which can indirectly improve this assessment component.

In conclusion, though upside delivery flexibility can not gain direct improvements, BIM still has some potentials to improve this component from higher flexibility, better collaboration, and systematic management.

7.3.3 Upside make adaptability

Upside make adaptability is used to determine the potential to maximize outcomes from a make process. For precast concrete, documentations and finished products are considered as the outcomes from a make process. The assessment focuses on the maximum percentage of a make capacity which can be achieved within the duration 30 days without a material constraint. For example, if a company can design and produce 100 pieces of products per month, what is the maximized percentage of design and production can be achieved within a month.

Compared design to production processes, design is generally a major time consuming process. As BIM affects design and planning processes directly, the productivity of design can be increased with higher accuracy and timeliness. The maximum capacity of a design process can be increased to the maximum capacity of a production process, such as maximum space for production, maximum equipment for concrete casting, and minimum duration for concrete curing. Furthermore, the manpower required for BIM is less than a conventional process. With limited space of working area, a BIM modeler can substitute more tasks for higher productivity.

In conclusion, similar to upside make flexibility, BIM has a great potential to improve upside make adaptability. The achievable improvements are resulted from faster working process, higher flexibility, less errors, less manpower required, and an automation.

7.3.4 Downside make adaptability

Downside make adaptability is used to determine a potential of a company to minimize capacity of make process without penalties. The assessment is used to determine the adaptability of an organization to deal with sluggish market situation. For example, if a precast concrete company design and produce 200 pieces of products per month with fixed cost of 100 pieces of product. The minimum quantity requires for basic cost is at 100 pieces of product with downside make adaptability score at 50%.

Though BIM implementation can reduce costs in make process from shortened process times, BIM actually benefits a company for a large quantity of information management. With less work, the quality of conventional outcomes can be increased, as the duration is not very limited. The benchmarked benefits between BIM and conventional are reduced. BIM also requires a higher cost for adoption, such as hardware, software, and training. With higher unit cost for implementation, BIM affects this assessment component in a negative way.

In conclusion, BIM implementation worsen downside make adaptability due to higher adoption and implementation costs. BIM is not suitable in some conditions, as it is unable to improve a precast concrete supply chain in every aspect.

7.3.5 Upside deliver adaptability

Upside deliver adaptability is used to determine the potential of a company to maximize its capacity of a deliver process. The assessment focuses on the maximum percentage of deliver capacity that can be achieved within the duration of 30 days without considering a finished product constraint. For example, if a precast concrete company can transport and erect 100 pieces of products per month, what is the maximum percentage of transportation and erection can be achieved within the same duration.

For the case study company, the maximum capacity of transportation and delivery can be increased by outsourcing working units from other companies. Therefore, the maximum capacity of BIM is indifferent from a conventional process.

However, as erection process requires an expertise, a three-dimensional visualization model of a BIM tool can be utilized for outsourced erection units. The design can be simplified with improved collaboration between multiple working units. BIM also reduce errors, which results in delays and costs. Using BIM, the delivery process can be improved indirectly from better management, but the maximum capacity of the delivery remains unchanged.

In conclusion, BIM can indirectly improve this assessment component if the company perform deliver process without outsourcing the tasks. The improvements are resulted from better collaboration and management. However, this assessment component is inessential for the case study company, as it is not constrained by limited resource as same as a make process.

It must also be noted that the results for agility is also depends on opinions of the interviewees towards BIM which may cause bias in the qualitative results.

7.4 Cost

Cost is the last supply chain assessment attribute for this research project. Using the cost framework provided by the SCOR model, costs in a supply chain can be benchmarked systematically. There are numerous cost factors presented in a supply chain assessment framework, which most of them are irrelevant to BIM implementation. There are two costs that actually associate with BIM in design process: labor cost and automation cost. It must be noted that cost data presented in this topic were partially modified to protect confidential information of the case study company.

Before calculating costs of the case study project, basic labor cost and basic automation cost were determined and converted into unit cost per hour. The unit of cost measurement was Thai baht (THB). The basic labor cost is presented in Table 7.4.

Table 7.4: Basic labor cost

Number of working day per year	260	days
Working duration per day	8	hours
Number of working hour per year	2080	hours

Cost (THB/year)	Conventional			BIM
	Engineer	Draftsman	Production	BIM modeler
Wage	276,000	216,000	336,000	300,000
Reward	23,000	18,000	28,000	25,000
Health insurance	-	-	-	-
Training cost	-	-	-	-
Social security	-	-	-	-
Other cost	-	-	-	-
Total (THB/year)	299,000	234,000	364,000	325,000
Unit labor cost (THB/hour)	**143.75**	**112.50**	**175.00**	**156.25**

For conventional process, engineer, draftsman, and production manager were responsible for tasks in design and planning processes. A BIM modeler must be substituted by the researcher for the tasks for these three working positions. Unit labor costs were converted to an hour basis. For an automation cost, a basic automation cost is presented in Table 7.5.

Table 7.5: Basic automation cost

Depreciation period of hardware	5	years
Depreciation period of software	5	years

Cost (THB)	Conventional	BIM
Hardware		
Mainboard, VGA, HDD, RAM, case…	35,000	40,000
Monitor	4,000	4,000
Mouse, keyboard, power supply, …	4,500	4,500
Software		
Autodesk AutoCAD (initial purchase)	50,000	-
Autodesk AutoCAD (yearly license)	2,000	-
Autodesk Revit (initial purchase)	-	250,000
Autodesk Revit (yearly license)	-	10,000
Microsoft Office	25,000	25,000
Google SketchUp	-	-
Other software	-	-
Maintenance		
System maintenance (yearly)	6,000	6,000
Total (THB/year)	26,600	75,900
Unit automation cost (THB/hour)	**12.79**	**36.49**

Based on the SCOR framework, costs must be distributed according to the depreciation rate of the case study company. The costs of hardware, software, and maintenance for both processes were summed and converted to an hour basis.

From the obtained data, a unit labor cost estimated for a BIM-based process was higher due to higher requirements of BIM and precast concrete expertise. It was also difficult to recruit a BIM modeler because BIM was still in the development phase in Thailand in the year this research was conducted. For unit automation cost, BIM cost was also higher due to higher requirements of both hardware and software.

After basic unit costs for labor and automation were collected, they were multiplied with the process time of each case study project. Using the data obtained for responsiveness, the total costs can be determined on a project basis. Table 7.6 and Table 7.7 presents the costs of case study project 01 and 02 respectively.

Table 7.6: Costs of case study project 01

Conventional		
Production drawing creation		
Labor cost	10,125.00	THB
Automation cost	1,150.96	THB
Assembly drawing creation		
Labor cost	1,780.88	THB
Automation cost	202.44	THB
Quantification		
Estimation sheet		
Labor cost	1,138.50	THB
Automation cost	101.28	THB
Reinforcement cut list		
Labor cost	2,392.25	THB
Automation cost	174.82	THB
Total conventional labor cost	**15,437**	**THB**
Total conventional automation cost	**1,630**	**THB**
Total conventional cost	**17,066**	**THB**

BIM		
Product model creation		
Labor cost	2,877.60	THB
Automation cost	672.03	THB
Assembly model creation		
Labor cost	598.96	THB
Automation cost	139.88	THB
Reinforcement creation		
Labor cost	4,609.38	THB
Automation cost	1,076.47	THB
Drawing creation		
Product assembly creation		
Labor cost	1,340.63	THB
Automation cost	313.09	THB
Sheet creation		
Labor cost	2,760.94	THB
Automation cost	644.79	THB
Documentation		
Labor cost	351.56	THB
Automation cost	82.10	THB
Total BIM labor cost	**12,539**	**THB**
Total BIM automation cost	**2,928**	**THB**
Total BIM cost	**15,467**	**THB**

The total costs for conventional and BIM-based processes for the case study project 01 were approximately 17,000 and 15,400 THB respectively.

Table 7.7: Costs of case study project 02

Conventional		
Production drawing creation		
Labor cost	8,493.75	THB
Automation cost	965.53	THB
Assembly drawing creation		
Labor cost	2,390.63	THB
Automation cost	271.75	THB
Quantification		
Estimation sheet		
Labor cost	1,473.44	THB
Automation cost	131.08	THB
Reinforcement cut list		
Labor cost	3,207.75	THB
Automation cost	234.41	THB
Total conventional labor cost	**15,566**	**THB**
Total conventional automation cost	**1,603**	**THB**
Total conventional cost	**17,168**	**THB**

BIM		
Product model creation		
Labor cost	3,020.83	THB
Automation cost	705.48	THB
Assembly model creation		
Labor cost	742.19	THB
Automation cost	173.33	THB
Reinforcement creation		
Labor cost	2,929.69	THB
Automation cost	684.19	THB
Drawing creation		
Product assembly creation		
Labor cost	1,457.81	THB
Automation cost	340.46	THB
Sheet creation		
Labor cost	3,034.38	THB
Automation cost	708.64	THB
Documentation		
Labor cost	273.44	THB
Automation cost	63.86	THB
Total BIM labor cost	**11,458**	**THB**
Total BIM automation cost	**2,676**	**THB**
Total BIM cost	**14,134**	**THB**

The total costs for conventional and BIM-based processes for the case study project 02 were approximately 17,100 and 14,100 THB respectively

It was obvious that the cost of design varies with times taken for different projects. Though both unit labor cost and automation cost were higher, total BIM cost for both projects were slightly lower due to shorter process times for design and planning processes. However, these cost reductions may vary for different project. Table 7.8 summarized cost improvements for both case study projects.

Table 7.8: Percentage improvement of cost

Case study project 01		
	Conventional	BIM
Labor cost	15,437 THB	12,539 THB
Automation cost	1,630 THB	2,928 THB
Total cost	17,066 THB	15,467 THB
Ratio of labor cost to automation cost	9.47	4.28
Percentage improvement (%)	**9.37**	

Case study project 02		
	Conventional	BIM
Labor cost	15,566 THB	11,458 THB
Automation cost	1,603 THB	2,676 THB
Total cost	17,168 THB	14,134 THB
Ratio of labor cost to automation cost	9.71	4.28
Percentage improvement (%)	**17.67**	

Using BIM, overall costs were reduced by 9.37% and 17.67% for the case study project 01 and 02 respectively. Compared labor cost to automation cost, it was found that an automation cost was much lower due to a long depreciation rate of the case study company. Therefore, the labor cost was actually a cost driver for BIM implementation. The ratio of labor cost to automation cost was also reduced significantly after BIM implementation.

Similar to reliability, cost improvements were also depend on various factors, such as reward policy, depreciation rate of a company, and existing condition of supply chain cost. However, the most influential factor that affect design and planning costs is the time spend for each process.

In addition, supply chain costs for design and planning processes also depends on the number of precast concrete structures in a project. The design may be used for a single house or a large group of similar houses. The unit cost for each project varies accordingly, for example, if the design of case study project 01 is used to construct 10 houses, the cost predesign is reduced ten times according to the quantity of production.

In conclusion, BIM has a great potential to improve costs in design and planning processes. Although process times of two case study projects were improved significantly at 36.98% and 41.49%, the improvements of cost are lower due to higher unit labor cost and unit automation cost. Supply chain costs were reduced slightly at approximately 9% and 17% for the case study project 01 and 02 respectively.

7.5 Summary

In this chapter, the supply chain performances resulting from BIM implementation are presented and explained. Based on the modified SCOR assessment framework, data for each supply chain attribute were collected, benchmarked, and analyzed. The problematic issues of each supply chain component were clarified with achievable solutions from BIM.

For reliability, perfect documentation can gain most improvements from BIM, as the component can gain benefits directly. BIM also has a potential to improve perfect quantity and perfect delivery indirectly from better collaboration and management. However, perfect condition can gain least impact from BIM, as the tasks for this component mostly rely on operational skills.

For responsiveness, BIM showed a great potential to minimize times for design and planning processes. The process times of case study projects were significantly reduced at 36.98% and 41.49% respectively. It was found that the design complexity is the most influential factor to the time requirements.

For agility, BIM shows great potential to upside make components, as BIM can improve design and planning processes significantly. For upside deliver components, BIM also shows some potential improve these components indirectly from better collaboration and management. However, for downside make component, BIM affect it in the opposite way. Using BIM worsen the component, as BIM requires higher cost for adoption and implementation. Without sufficient amount of works, BIM is unable to benefit a precast concrete supply chain.

For cost, the total costs of the case study project 01 and 02 were reduced slightly at 9.37% and 17.67% respectively. Though process times required for project 01 and 02 were improved significantly, the cost improvements were lower due to higher unit cost for implementation. Using BIM, the ratio of cost spend for manual process to automation process was reduced. It was also found that an actual cost driver for BIM implementation is a labor cost, instead of an automation cost. However, it must be noted that the calculated project cost still depend on the quantity of the construction for each design. BIM should be preferred for mass-production instead of customized production to maximize its benefits.

The results obtained are based on the practices of the case study company. It must also be noted that the supply chain improvements also depend on various factors, such as expertise of a BIM modeler, bias of the interviewees, type of projects, complexity of the design, and existing condition of a conventional process. In addition, the supply chain performances of BIM-based case study projects show great improvements due to the repetitions of the product design. The prepared database was suitable for a model development of the case study projects.

CHAPTER VIII
CONCLUSIONS

8.1 Research Conclusions

This research project proposed BIM implementation and assessment for a precast concrete supply chain. The research has three major concerns: BIM, precast concrete supply chain, and supply chain assessment framework. The case study precast concrete company and a BIM tool were selected for the research. A BIM model development process for precast concrete contractor was proposed and compared to determine an optimal one. The model development has three major concerns: to create a precast concrete BIM model which can be utilized for both production and construction aspects, to maximize BIM benefits from a selected BIM tool, and to simplify working processes for BIM. The assessment framework was prepared based on the SCOR standard version 11.0 to determine supply chain improvements resulting from BIM implementation. Then, BIM was implemented on two precast concrete housing projects.

After BIM implementation, major outcomes for documentation were generated from the developed BIM models: production drawing, assembly drawing, estimation sheet, reinforcement cut list, and schedule. They were compared with outcomes from a conventional process to determined improvements. The supply chain data were collected, benchmarked, and concluded.

The comparison of documentation outcomes from BIM versus conventional process showed that BIM is superior for accuracy and timeliness. The working process was also simplified with less manpower required. For the supply chain assessment, most of supply chain attributes can gain improvements from BIM, especially for cost and time. However, the results obtained from BIM implementation can vary due to various factors, such as an expertise of labor, type of precast concrete product, complexity of the design, potential of a BIM tool, and existing performances of the conventional supply chain.

BIM implementation for precast concrete contractors must start from the basic requirements, such as creating production drawings, creating assembly drawings, and quantifying materials, before implementing BIM to other fields. For example, if a user requires to manage information of a quality control unit, these information items relevant to quality control tasks can be included in a BIM model. If BIM can not be utilized to fulfill basic requirements, then it can not be utilized further to other fields.

For precast concrete contractors, a major factor for a BIM adoption is not the quantity of a production. The complexity of the design must be a major criteria for BIM adoption. With high complexity of design, BIM can show most potentials for its visualization, clash detection, quantification, collaboration, and supply chain integration. Precast concrete contractors can maximize benefits from BIM for the engineered-to-order products, such as precast beam, precast column, precast tray, precast stair, and precast wall. In the same way, it is unnecessary for a precast concrete contractor to implement BIM to every product in its business. The products should be selected based on a design complexity to avoid unnecessary tasks.

The level of detail for a BIM model is another concern for a model development. It was found that a BIM model required for production tasks should reach the levels of detail at 350 or 400. If the level of detail is lower than 350, a BIM model is fallible for errors in production and erection.

It was also found that a proper BIM adoption is the most influential key to implement BIM successfully in a precast concrete supply chain. BIM implementation process must be designed thoroughly to manage information items systematically. The database must be prepared comprehensively with a manual for utilization. Trainings are required for labor preparation. Finally, with proper preparation, BIM implementation can be simplified with maximized benefits.

This research provides various contributions in the fields of BIM and a precast concrete supply chain management. The knowledge from this research can be served as a guideline to develop a BIM model specifically for precast concrete contractors. The overall supply chain management for precast concrete industry can be improved in the field of information management. The positive outcomes obtained from the implementation also enhance BIM adoption for the precast concrete industry.

8.2 Research Limitations

i) Insufficient duration for BIM adoption

In general, a BIM adoption process takes years for a company to achieve its full potential. BIM requires a comprehensive database, changes in working process, expertise of labor, etc. for successful implementation. The time for this research project was limited to a year, which BIM can still develop further for different tasks, such as structural analysis, delivery management, and automated inventory management. With longer duration for implementation, the outcomes of supply chain performances can be improved further.

ii) Lack of BIM functions for production aspect

The BIM tool used was imperfect for precast concrete contractors in the year this research was conducted. Based on the selected BIM tool, the functions required for production tasks were absent. These functions were substituted by manual processes, which were time consuming and fallible. With a proper tool, process times for quantification and documentation can be minimized from an automation.

iii) Unavailability of supply chain data

In general, the research projects concerning supply chain management deal with broad views of a whole company, which the data required are confidential in nature. For example, the cost data were unavailable and required to be estimated for the assessment.

iv) Confidential issues for collaboration

Using BIM, some confidential information, such as technical design of precast concrete connections, were included in a BIM model. These information can not be shared with other companies. Due to this confidential issues, BIM models could not be used for a direct collaboration with external stakeholders in a supply chain.

8.3 Suggestions

In the year this research was conducted, BIM was very new in Thailand, especially for precast concrete contractors. BIM should be investigated further in details for each task in the production process. For example, BIM can be implemented and automated between design and production using a modern production equipment. Also, BIM still has potential to push design and planning processes to a complete automation. Precast concrete contractors can realize actual benefits of BIM from maximized automation.

Quality control in a precast concrete industry is another topic which requires to manage large amount of information. BIM also has potential to be utilized further in this field. Quality control documentation must be converted from paper-based to digital-based and collaborate with a BIM model.

Furthermore, the research should be conducted on a case study company which undergoes a mass production. It is obvious that some results, such as supply chain costs, can improved further with an appropriate type of projects for implementation. For a supply chain, a proper standard which concerns information management is still absent. The topic should be investigated further to improve the standard of supply chain management.

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APPENDIX

APPENDIX A

INFORMATION FLOW OF THE DESIGN DATABASE

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INFORMATION FLOW OF THE DESIGN DATABASE

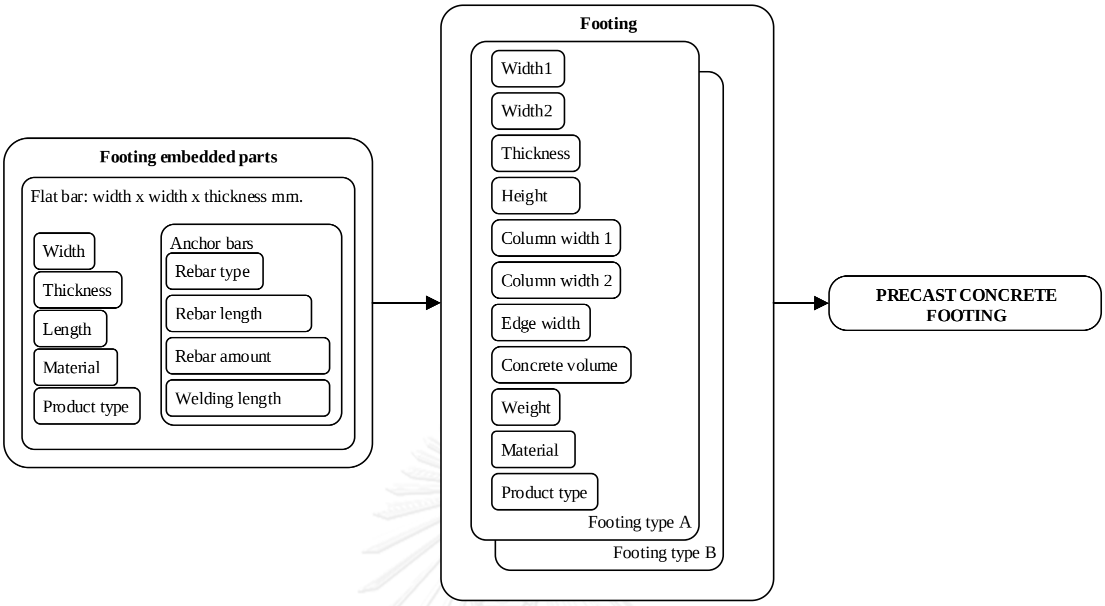

Figure A.1: Information flow of precast concrete footing

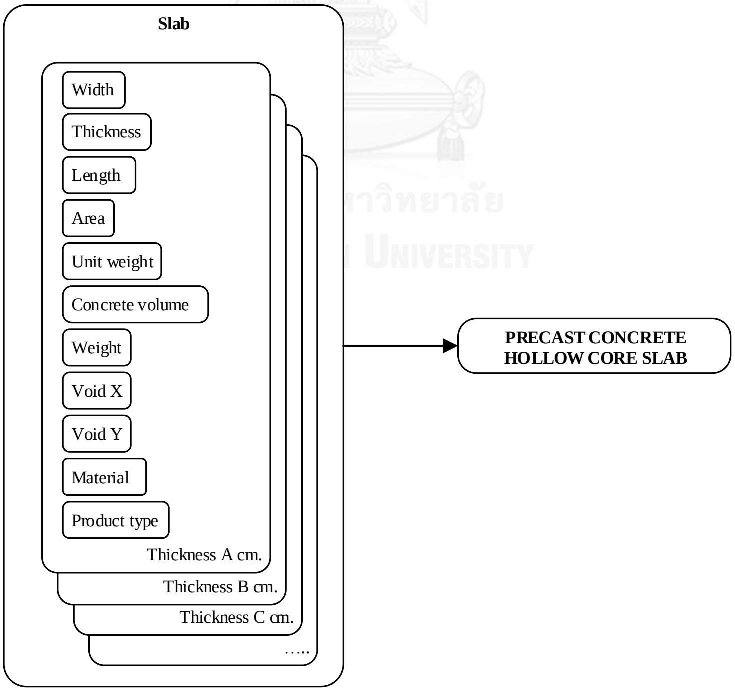

Figure A.2: Information flow of precast concrete slab

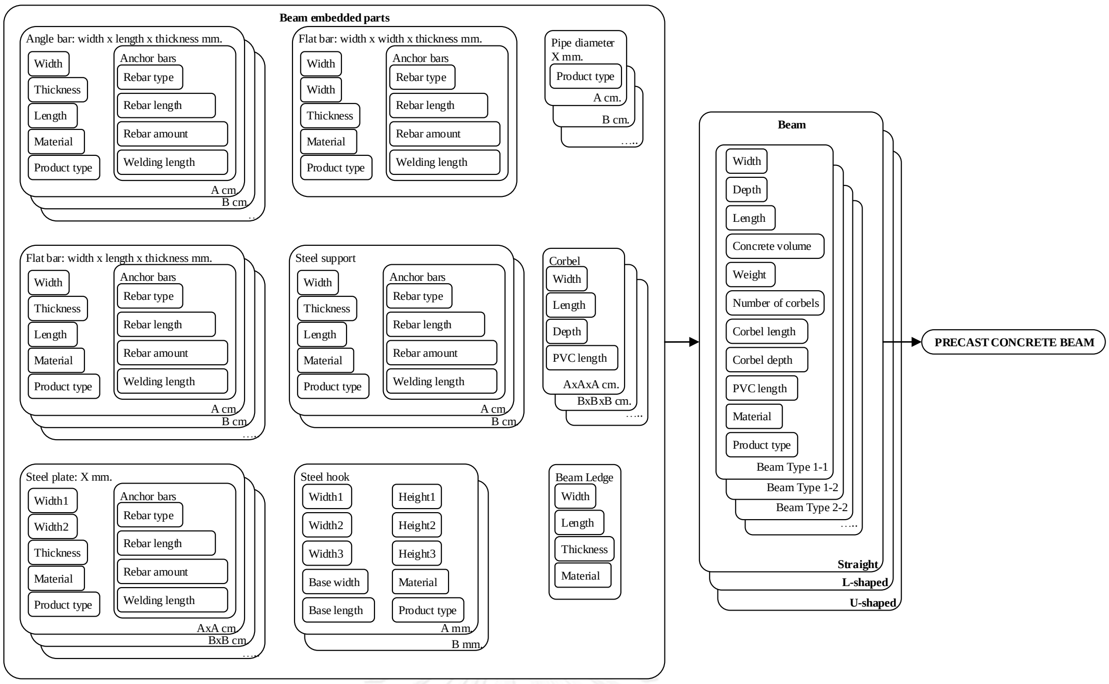

Figure A.3: Information flow of precast concrete beam

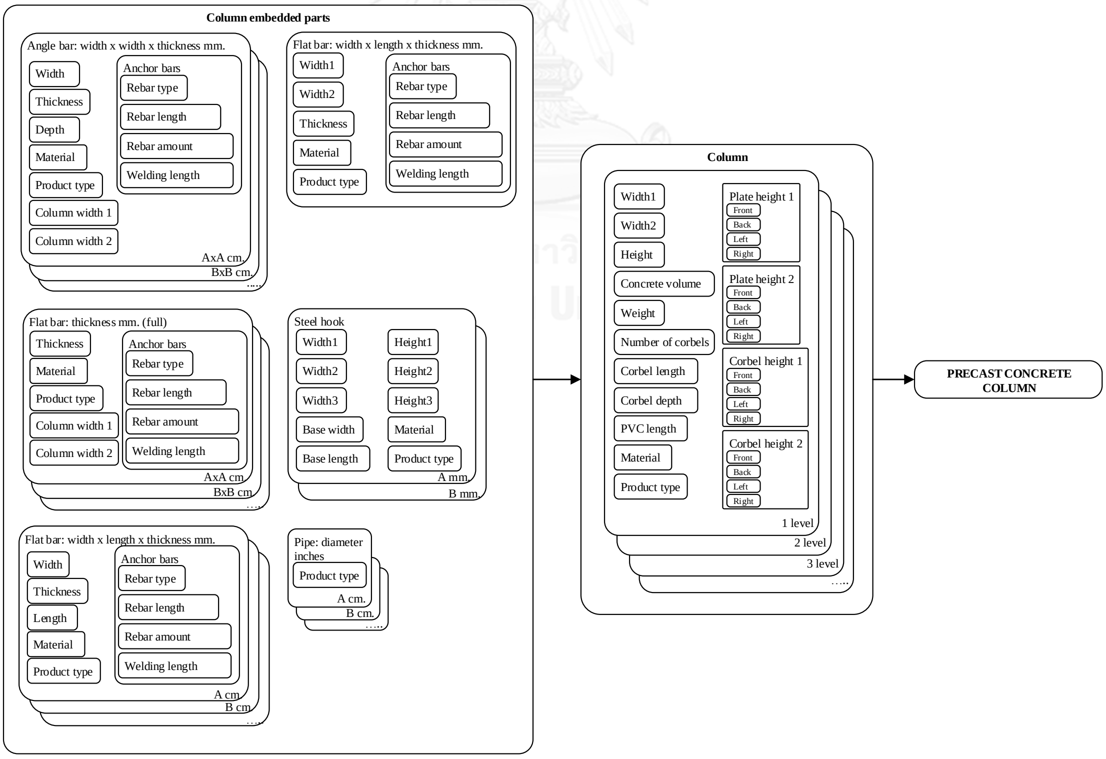

Figure A.4: Information flow of precast concrete column

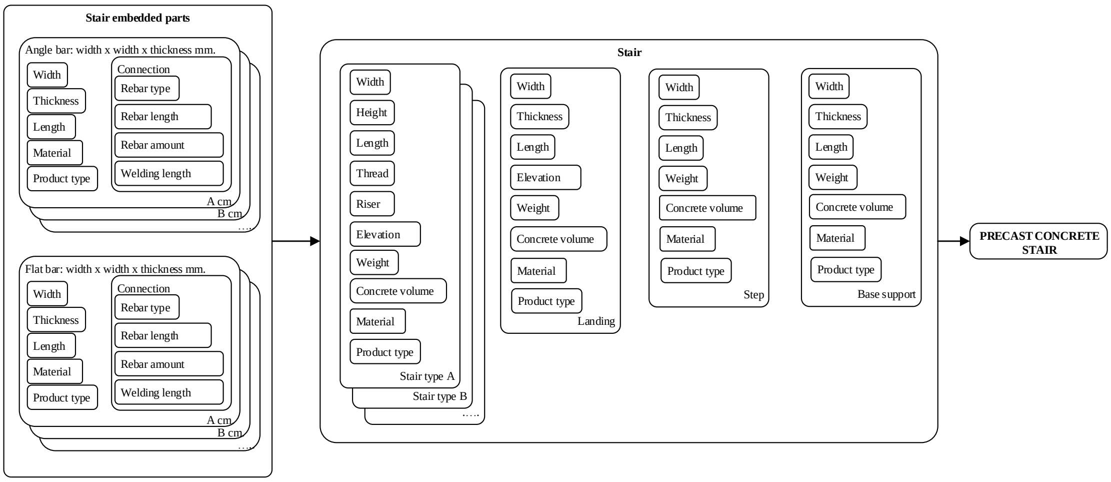

Figure A.5: Information flow of precast concrete stair

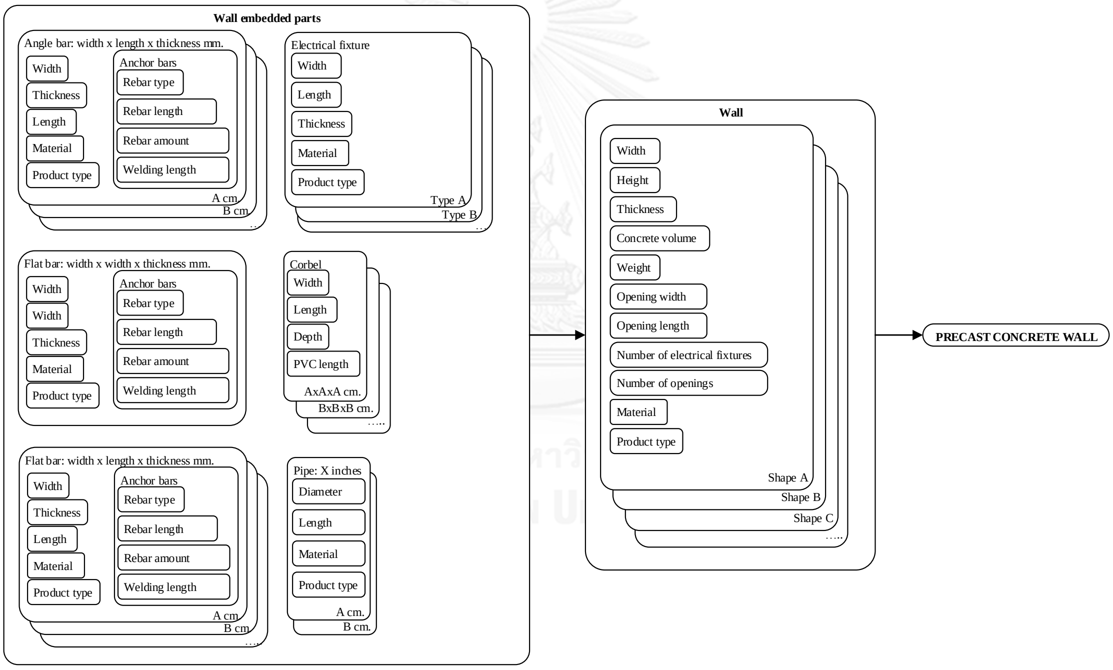

Figure A.6: Information flow of precast concrete wall

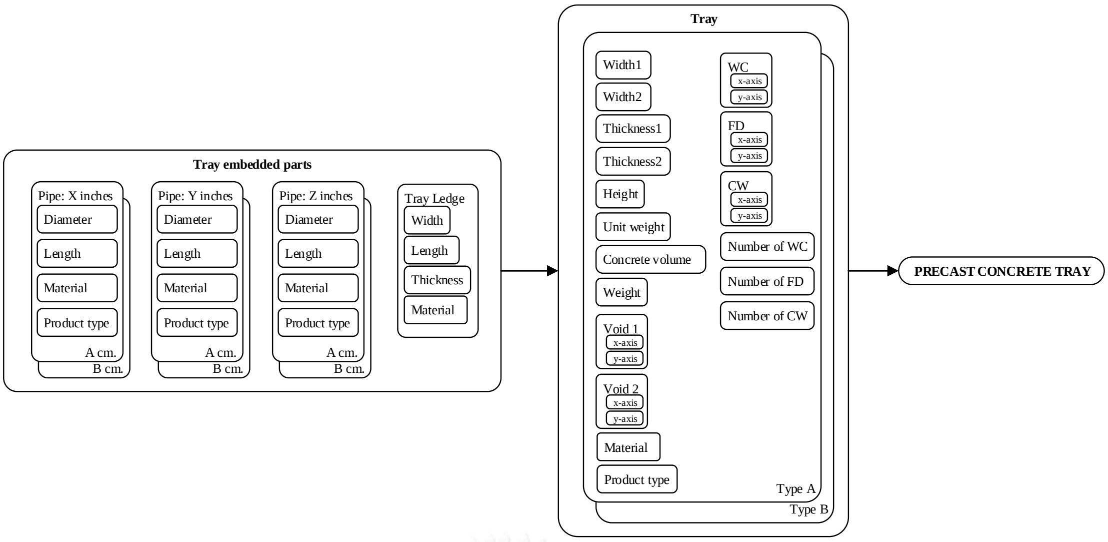

Figure A.7: Information flow of precast concrete tray

APPENDIX B
OUTCOMES GENERATED FROM A BIM MODEL

APPENDIX B

OUTCOMES GENERATED FROM A BIM MODEL

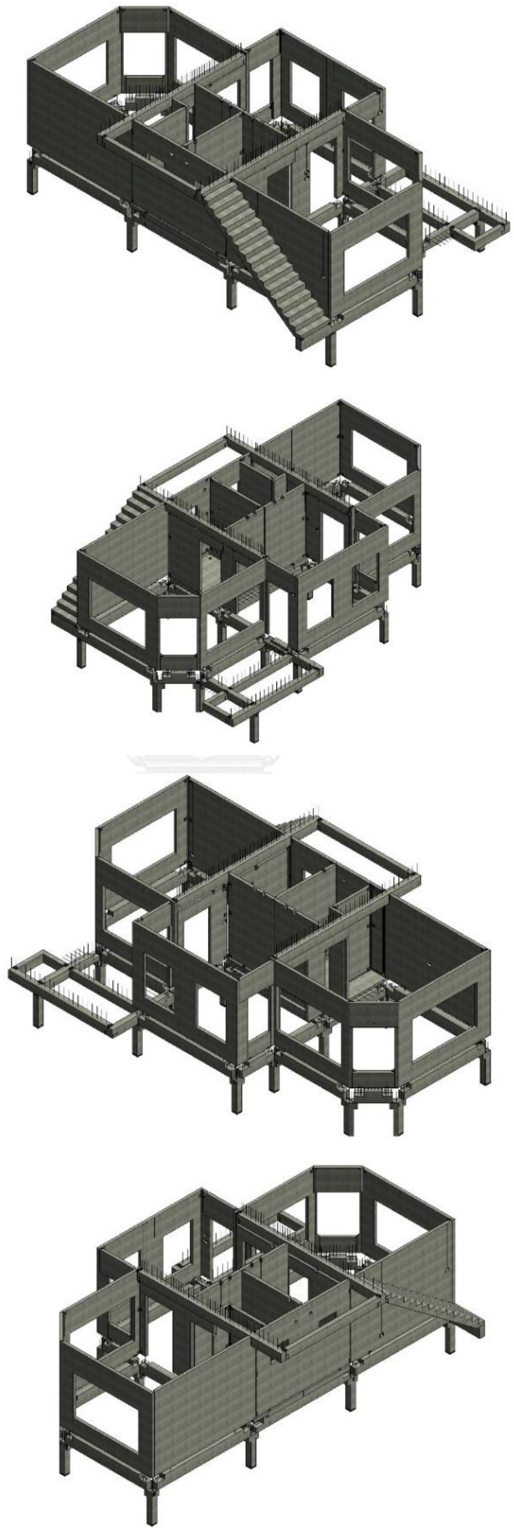

Figure B.1: Three-dimensional images of case study project 01

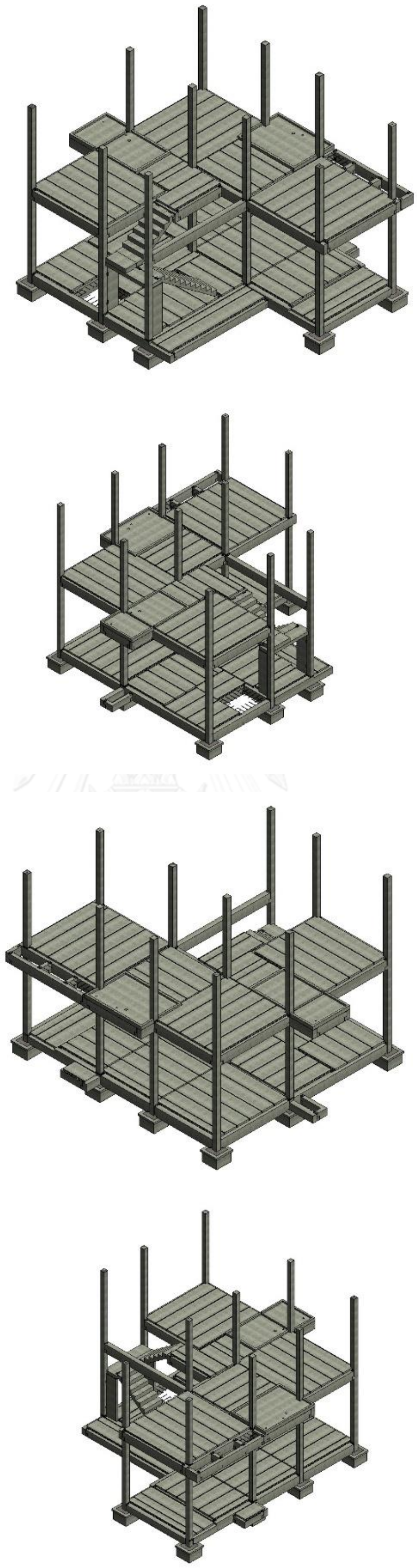

Figure B.2: Three-dimensional images of case study project 02

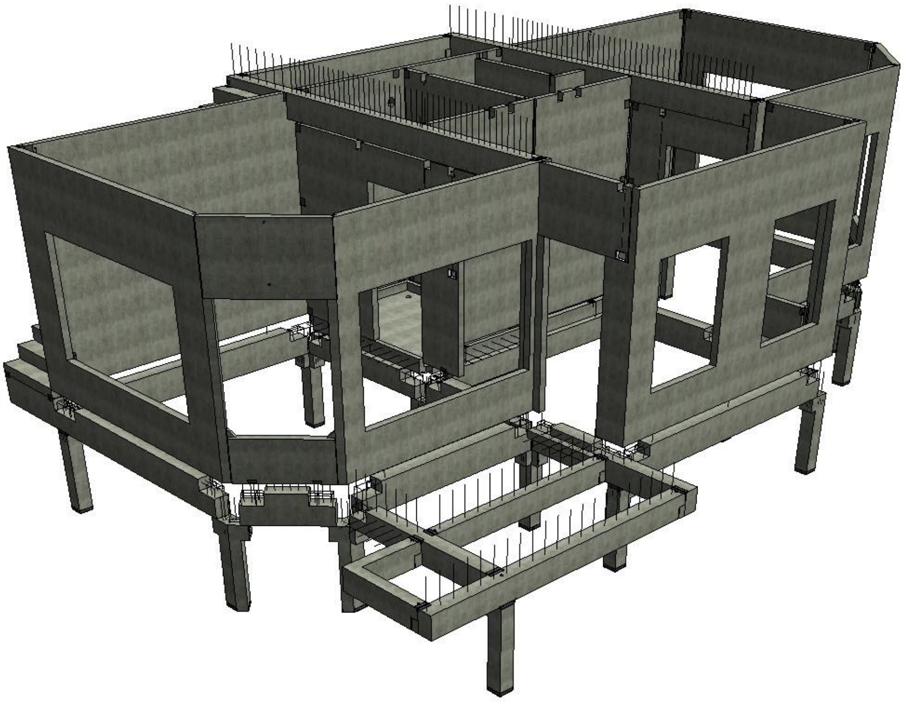

Figure B.3: Perspective image of case study project 01

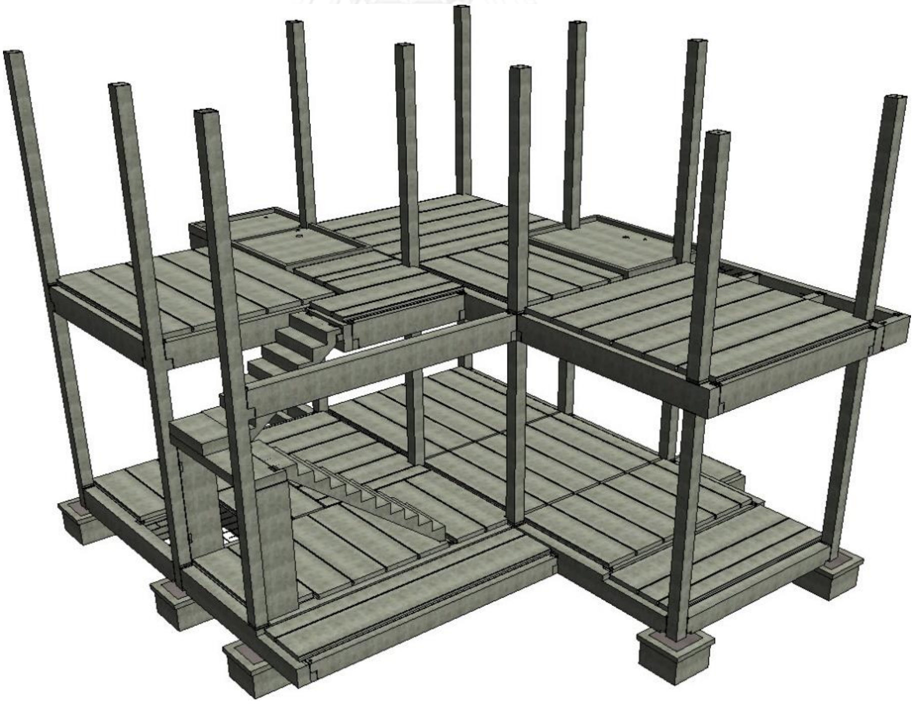

Figure B.4: Perspective image of case study project 02

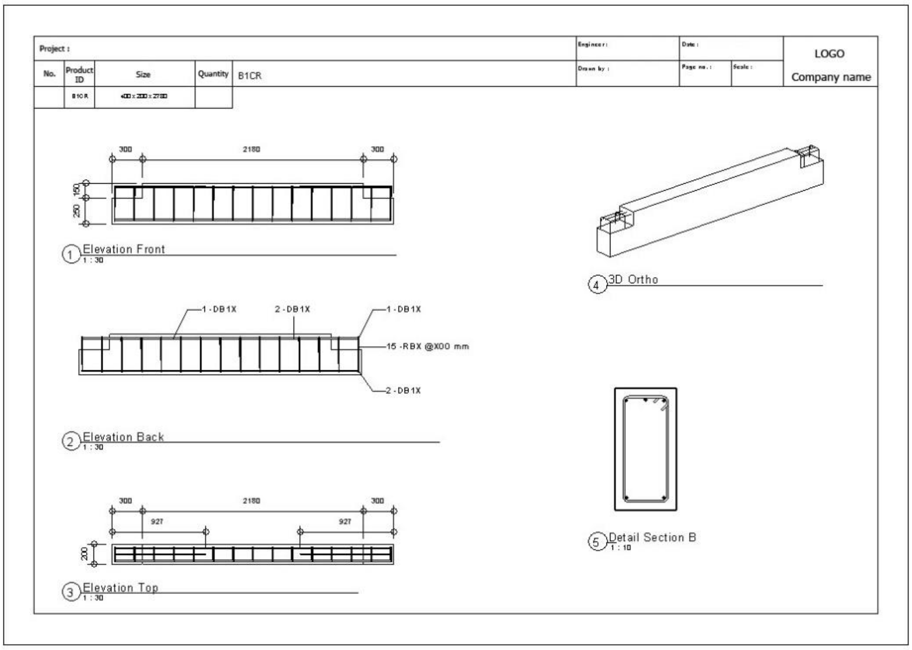

Figure B.5: Example of production drawing: beam

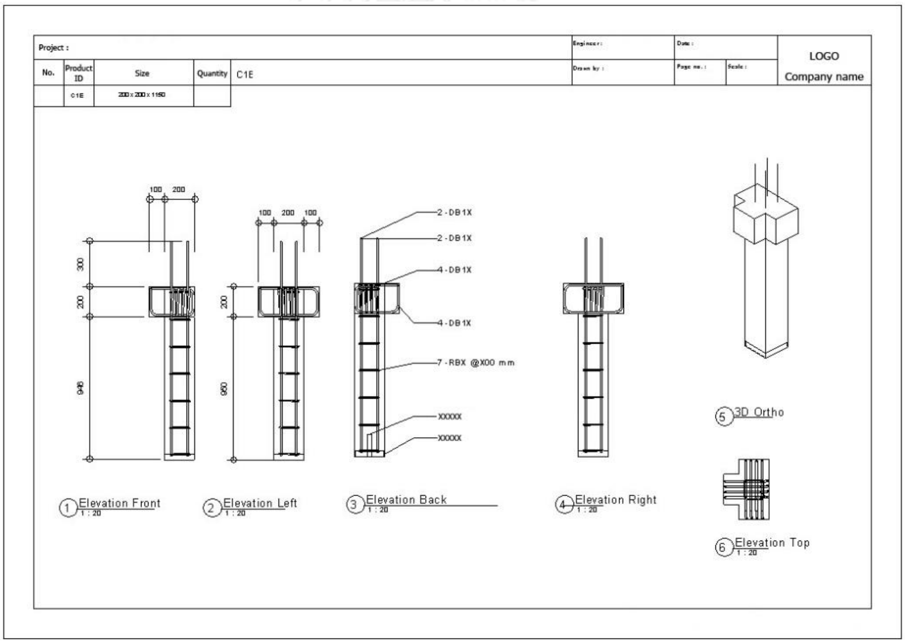

Figure B.6: Example of production drawing: column

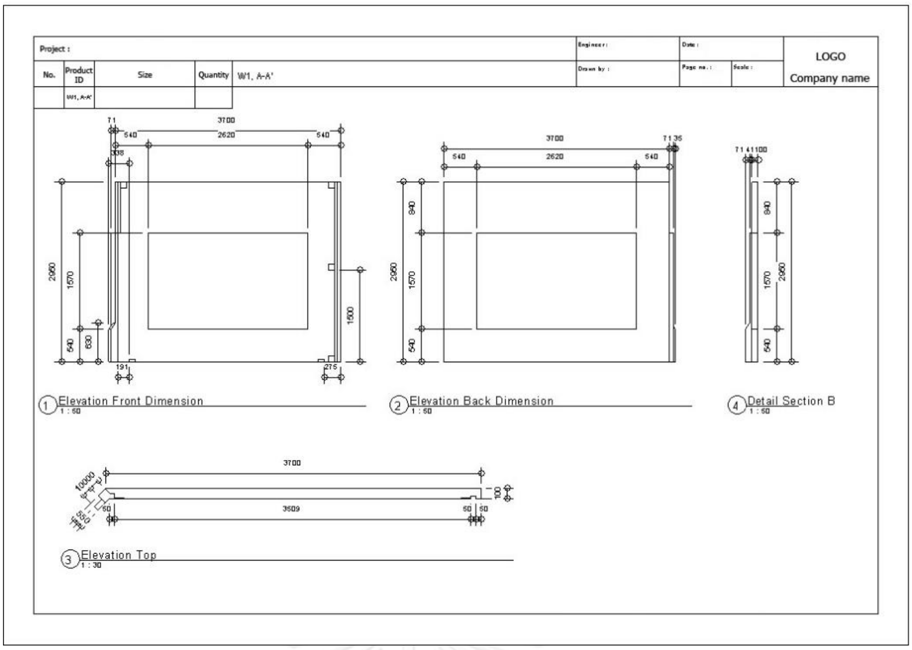

Figure B.7: Example of production drawing: wall

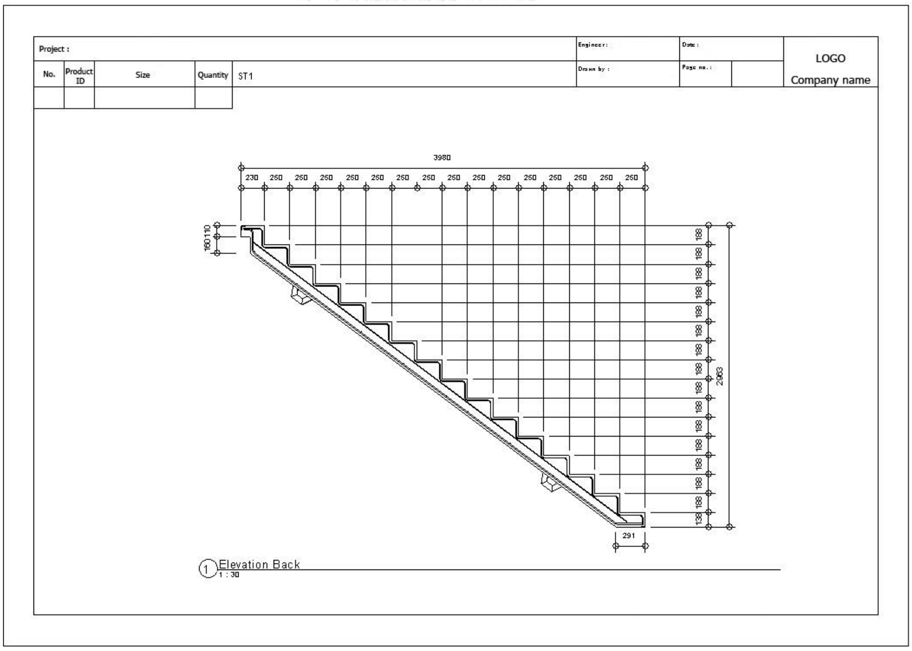

Figure B.8: Example of production drawing: stair

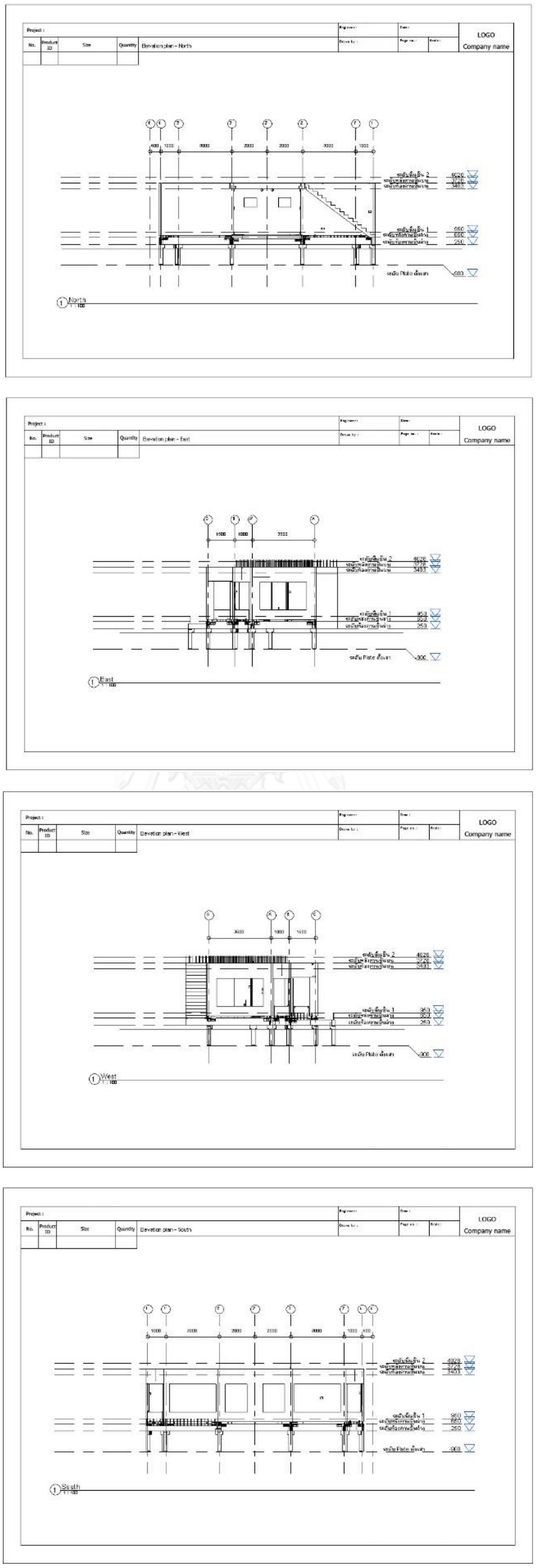

Figure B.9: Example of assembly drawings: elevation view

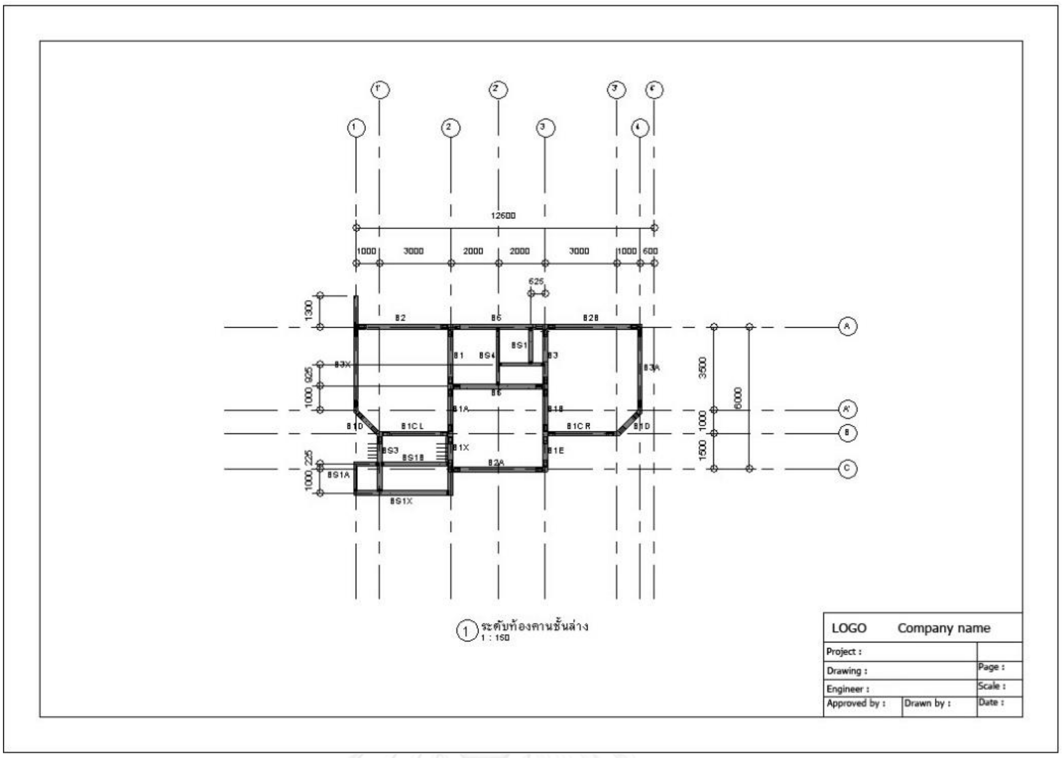

Figure B.10: Example of assembly drawing: beam

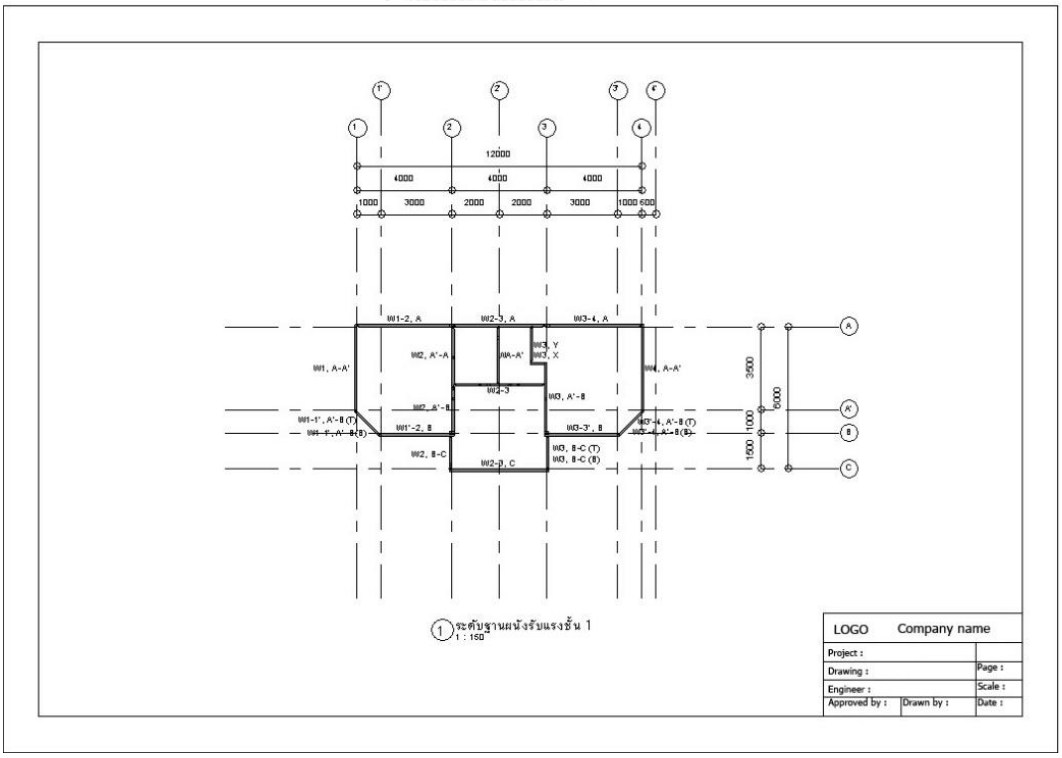

Figure B.11: Example of assembly drawing: wall

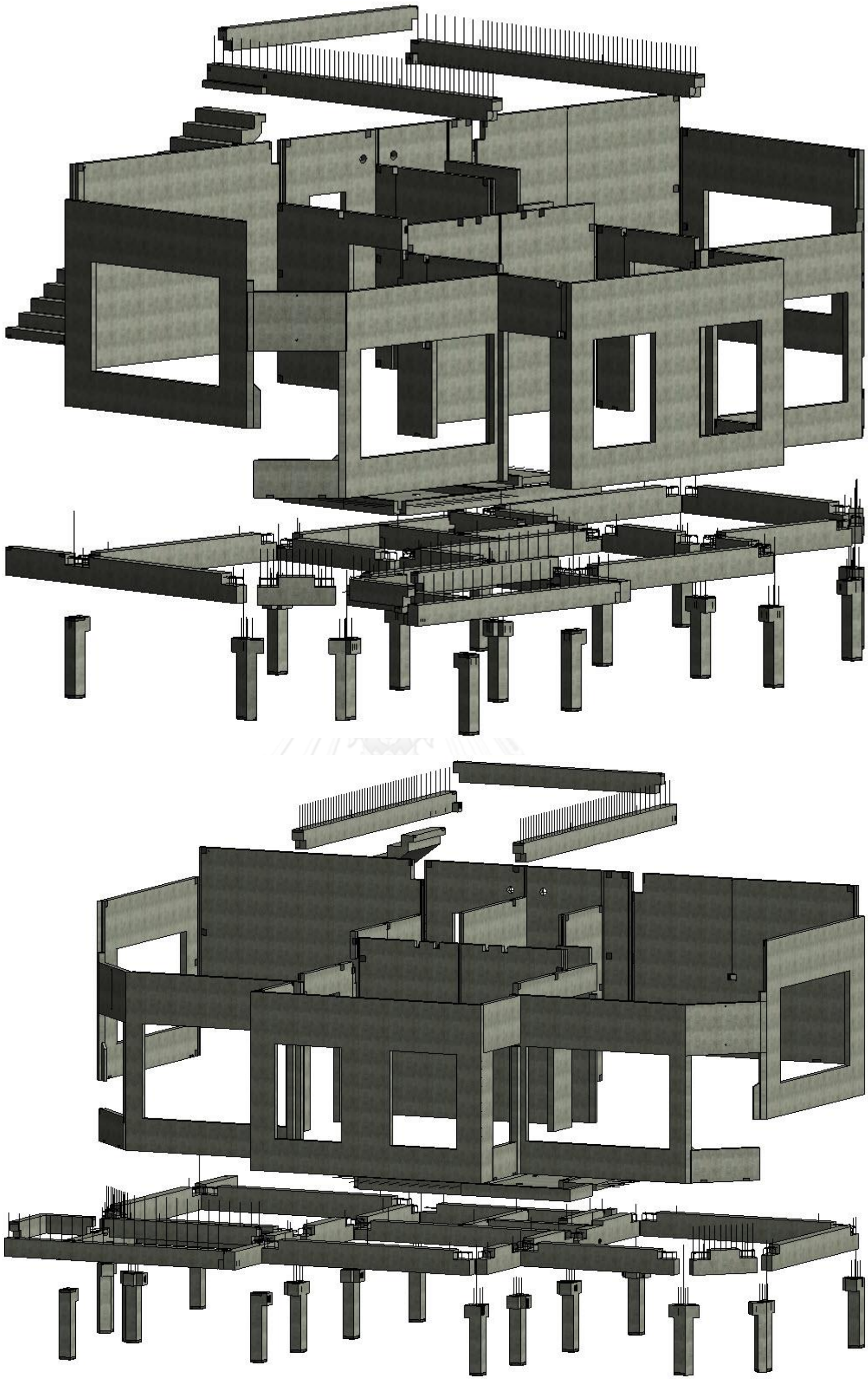

Figure B.12: Three-dimensional images of disassemble precast products

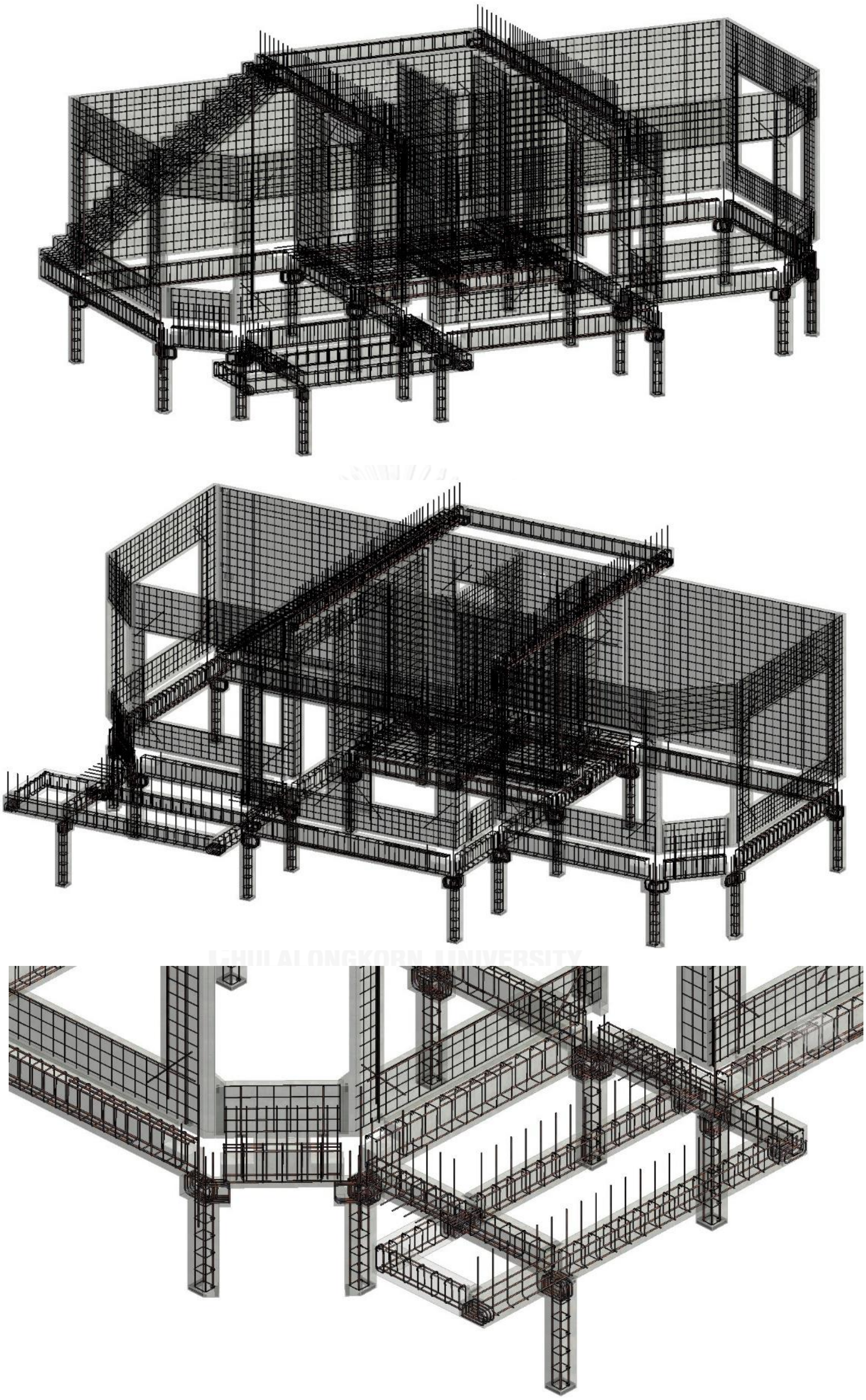

Figure B.13: Three-dimensional images of reinforcement bar

Table B.1: Example of product list: beam

Beam list										
Product ID	Type	Corbels	Dimensions					Concrete volume	Weight
			Width	Thickness	Length 1	Length 2	Total length		
Level 1									
B1	3-3	0	0.20	0.33	2.28	-	2.28	0.13 m³	312.48 kg
B1A	3-3	0	0.20	0.40	1.78	-	1.78	0.12 m³	298.56 kg
B1B	3-3	0	0.20	0.40	1.78	-	1.78	0.12 m³	298.56 kg
B1CL	3-3	0	0.20	0.40	2.78	-	2.78	0.20 m³	490.56 kg
B1E	3-3	0	0.20	0.40	1.28	-	1.28	0.08 m³	202.56 kg
B1X	3-3	2	0.20	0.40	2.49	-	2.49	0.17 m³	402.48 kg
B2	3-3	0	0.20	0.40	3.78	-	3.78	0.28 m³	682.56 kg
B2A	3-3	0	0.20	0.40	3.78	-	3.78	0.28 m³	682.56 kg
B2B	3-3	0	0.20	0.40	3.78	-	3.78	0.28 m³	682.56 kg
B3	3-3	1	0.20	0.40	2.28	-	2.28	0.15 m³	367.20 kg
B3A	3-3	0	0.20	0.40	3.28	-	3.28	0.24 m³	586.56 kg
B3X	3-0	0	0.20	0.40	4.69	-	4.69	0.37 m³	878.88 kg
B5	3-3	1	0.20	0.33	3.78	-	3.78	0.23 m³	551.88 kg
B6	3-3	2	0.20	0.33	3.78	-	3.78	0.23 m³	557.28 kg
BS1	2-2	0	0.15	0.33	1.38	-	1.38	0.06 m³	150.66 kg
BS1B	2-2	0	0.15	0.30	2.78	-	2.78	0.12 m³	289.44 kg
BS1X	2-0	1	0.20	0.30	3.99	-	3.99	0.24 m³	572.76 kg
BS2	2-2	1	0.15	0.33	1.80	-	1.8	0.09 m³	205.20 kg
BS3	3-0	2	0.20	0.30	2.28	-	2.28	0.13 m³	317.52 kg
BS4	2-2	1	0.15	0.33	2.28	-	2.28	0.11 m³	261.36 kg
B1CR	3-3	0	0.20	0.40	2.78	-	2.78	0.20 m³	490.56 kg
B1D	3-3	0	0.20	0.40	1.11	-	1.11	0.07 m³	169.92 kg
B1D	3-3	0	0.20	0.40	1.11	-	1.11	0.07 m³	169.92 kg
BS1A	2-2	0	0.15	0.30	1.19	0.99	2.18	0.09 m³	208.44 kg
								4.10 m³	
Level 2									
BS9X	2-0	1	0.20	0.33	5.79	-	5.79	0.38 m³	901.44 kg
BS9Y	2-0	1	0.20	0.33	5.79	-	5.79	0.38 m³	901.44 kg
BS1Y	2-2	0	0.15	0.33	3.78	-	3.78	0.18 m³	431.46 kg
								0.93 m³	
							Total	**5.03 m³**	

Table B.2: Example of product list: column

Column list						
Product ID	**Dimensions**			Corbels	Concrete volume	Weight
	Width 1	Width 2	Height			
Level 1						
C1	0.20	0.20	1.15	1	0.05 m³	120.00 kg
C1	0.20	0.20	1.15	1	0.05 m³	120.00 kg
C1	0.20	0.20	1.15	1	0.05 m³	120.00 kg
C1A	0.20	0.20	1.15	2	0.05 m³	129.60 kg
C1B	0.20	0.20	1.15	2	0.05 m³	129.60 kg
C1C	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1D	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1E	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1E	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1E	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1E	0.20	0.20	1.15	3	0.06 m³	139.20 kg
C1F	0.20	0.20	1.15	3	0.05 m³	129.60 kg
C1G	0.20	0.20	1.15	2	0.05 m³	129.60 kg
C1H	0.20	0.20	1.15	2	0.05 m³	129.60 kg
C1J	0.20	0.20	1.15	2	0.05 m³	129.60 kg
				Total	**0.82 m³**	

Table B.3: Example of product list: wall

Wall list					
Product ID	**Dimensions**			Concrete volume	Weight
	Width	Thickness	Height		
Level 1					
W2-3, C	4.20	0.10	2.95	1.24 m³	2973.60 kg
W2-3, A	3.78	0.10	2.91	1.10 m³	2639.95 kg
W2-3	3.78	0.10	2.89	1.09 m³	2621.81 kg
W3'-4, A'-B(B)	1.20	0.10	0.54	0.06 m³	155.52 kg
W4, A-A'	3.70	0.10	2.95	1.09 m³	2619.60 kg
W1, A-A'	3.70	0.10	2.95	1.09 m³	2619.60 kg
W1-1', A'-B(B)	1.20	0.10	0.54	0.06 m³	155.52 kg
W1-1', A'-B(T)	1.41	0.10	0.84	0.12 m³	284.26 kg
W1'-2, B	3.20	0.10	2.95	0.94 m³	2265.60 kg
W2, B-C	1.38	0.10	0.80	0.11 m³	264.96 kg
W1-2, A	4.09	0.10	2.95	1.21 m³	2895.72 kg
W3-4, A	4.09	0.10	2.95	1.21 m³	2895.72 kg
W3, B-C(B)	0.92	0.10	0.54	0.05 m³	119.23 kg
W3, B-C(T)	1.38	0.10	0.80	0.11 m³	264.96 kg
W3-3', B	3.20	0.10	2.95	0.94 m³	2265.60 kg
W3'-4, A'-B(T)	1.41	0.10	0.84	0.12 m³	284.26 kg
W2, A'-A	2.54	0.10	2.56	0.65 m³	1560.58 kg
W2, A'-B	2.04	0.10	2.60	0.53 m³	1272.96 kg
W3, A'-B	2.99	0.10	2.60	0.78 m³	1865.76 kg
W3, X	0.70	0.10	2.89	0.20 m³	485.52 kg
W3, Y	1.48	0.10	2.89	0.43 m³	1026.53 kg
WA-A'	2.38	0.10	2.89	0.69 m³	1650.77 kg
			Total	**13.83 m³**	

Table B.4: Example of reinforcement steel list based on products

Reinforcement list: product based									
Rebar size	Rebar shape	Length	Quantity	Total length	@ distance	Distance			
						A	B	C	D
BEAM									
B1									
DB1X	L-shape	0.75	1	0.75	-	-	0.32 m	0.43 m	-
DB1X	Straight	0.76	1	0.76	-	-	0.76 m	-	-
DB1X	Straight	2.23	2	4.46	-	-	2.23 m	-	-
RBX	Square	0.89	13	11.57	20 cm	0.04 m	0.28 m	0.15 m	0.28 m
B1A									
DB1X	Straight	0.59	1	0.59	-	-	0.59 m	-	-
DB1X	L-shape	0.72	1	0.72	-	-	0.33 m	0.43 m	-
DB1X	L-shape	0.73	1	0.73	-	-	0.28 m	0.49 m	-
DB1X	Straight	1.73	2	3.46	-	-	1.73 m	-	-
RBX	Square	1.04	10	10.40	20 cm	0.04 m	0.35 m	0.15 m	0.35 m
B1B									
DB1X	Straight	0.59	1	0.59	-	-	0.59 m	-	-
DB1X	L-shape	0.73	1	0.73	-	-	0.43 m	0.34 m	-
DB1X	L-shape	0.75	1	0.75	-	-	0.51 m	0.28 m	-
DB1X	Straight	1.73	2	3.46	-	-	1.73 m	-	-
RBX	Square	1.04	10	10.40	20 cm	0.04 m	0.35 m	0.15 m	0.35 m
B1CL									
DB1X	L-shape	0.73	1	0.73	-	-	0.28 m	0.49 m	-
DB1X	L-shape	0.74	1	0.74	-	-	0.49 m	0.28 m	-
DB1X	Straight	0.93	1	0.93	-	-	0.93 m	-	-
DB1X	Straight	2.73	2	5.46	-	-	2.73 m	-	-
RBX	Square	1.04	15	15.60	20 cm	0.04 m	0.35 m	0.15 m	0.35 m
B1CR									
DB1X	Straight	0.90	1	0.90	-	-	0.90 m	-	-
DB1X	Straight	2.72	2	5.44	-	-	2.72 m	-	-
DB1X	Straight	2.73	2	5.46	-	-	2.73 m	-	-
RBX	Square	1.04	15	15.60	20 cm	0.04 m	0.35 m	0.15 m	0.35 m
B1D									
DB1X	Straight	0.35	1	0.35	-	-	0.35 m	-	-
DB1X	L-shape	0.73	1	0.73	-	-	0.35 m	0.38 m	-
DB1X	Straight	1.05	2	2.10	-	-	1.05 m	-	-
DB1X	Straight	1.06	2	2.12	-	-	1.06 m	-	-
RBX	Square	1.04	7	7.28	20 cm	0.04 m	0.35 m	0.15 m	0.35 m
RBX	Straight	0.78	12	9.36	10 cm	-	0.78 m	-	-
…	...	…	…	…	…	…	…	…	…

Table B.5: Example of reinforcement steel list based on rebar size

Reinforcement list: size based					
Rebar shape	Length	Quantity per group	Total length	@ distance	Number of group
Cauldron X mm.					
Straight	0.16 m	-	2.40 m	20 cm	2
U-shape	0.21 m	4	0.84 m	20 cm	1
U-shape	0.34 m	-	12.24 m		4
U-shape	0.35 m	-	5.95 m	20 cm	2
U-shape	0.36 m	-	6.12 m	20 cm	2
		Total	**27.55 m**		
Cauldron X mm.					
Straight	0.19 m	15	2.85 m	15 cm	1
Straight	0.20 m	15	3.00 m	15 cm	1
Straight	0.22 m	-	3.96 m	-	2
Straight	0.23 m	12	5.52 m	15 cm	2
Straight	0.24 m	11	2.64 m	15 cm	1
Straight	0.28 m	-	3.92 m	-	2
Straight	0.29 m	15	4.35 m	15 cm	1
Straight	0.37 m	-	9.99 m	-	2
Straight	0.38 m	11	8.36 m	15 cm	2
Straight	0.39 m	-	8.97 m	15 cm	2
Straight	0.40 m	-	9.20 m	15 cm	3
Straight	0.43 m	11	4.73 m	15 cm	1
Straight	0.46 m	18	8.28 m	15 cm	1
Straight	0.47 m	27	12.69 m	10 cm	1
Straight	0.48 m	-	21.12 m	15 cm	4
Straight	0.49 m	-	28.42 m	-	6
Straight	0.54 m	6	3.24 m	15 cm	1
Straight	0.64 m	15	9.60 m	15 cm	1
Straight	0.65 m	15	19.50 m	15 cm	2
Straight	0.73 m	9	13.14 m	15 cm	2
Straight	0.75 m	-	34.50 m	-	3
Straight	0.77 m	-	25.41 m	15 cm	4
Straight	0.78 m	18	14.04 m	15 cm	1
Straight	0.79 m	-	16.59 m	15 cm	2
Straight	0.80 m	18	14.40 m	15 cm	1
Straight	0.81 m	11	8.91 m	15 cm	1
Straight	1.04 m	2	2.08 m	15 cm	1
Straight	1.05 m	5	10.50 m	15 cm	2
Straight	1.12 m	4	4.48 m	15 cm	1
Straight	1.14 m	2	4.56 m	15 cm	2
Straight	1.15 m	-	60.95 m	-	8
Straight	1.18 m	6	7.08 m	15 cm	1
Straight	1.23 m	6	7.38 m	15 cm	1
…	…	…	…	…	…

Table B.6: Example of master schedule

Master schedule							
Product	Product ID	Production schedule		Transportation schedule		Erection schedule	
		Plan	Actual	Plan	Actual	Plan	Actual
Level 01							
Column	C1	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1A	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1B	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1C	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1D	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1E	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1E	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1E	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1E	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1F	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1G	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1H	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1I	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Column	C1J	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1A	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1B	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1CL	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1E	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1X	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B2	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B2A	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B2B	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B3	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B3A	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B3X	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B5	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B6	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS1	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS1B	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS2	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS3	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS4	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1CR	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1D	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	B1D	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
Beam	BS1A	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD	2015.MM.DD
…	…				…	…	…

Table B.7: Example of production schedule

Production schedule							
Product	Product ID	Production Sequence	Production schedule		Production status		
			Plan	Actual	Preparation	Casting	Approval
Level 01							
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1A	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1B	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1C	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1D	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1F	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1G	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1H	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1I	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1J	2	2015.MM.DD	2015.MM.DD	✓	✓	
Beam	B1	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1A	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1B	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1CL	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1E	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1X	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B2	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2A	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2B	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3A	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3X	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B5	5	2015.MM.DD	2015.MM.DD			
Beam	B6	5	2015.MM.DD	2015.MM.DD			
Beam	BS1	5	2015.MM.DD	2015.MM.DD			
Beam	BS1B	5	2015.MM.DD	2015.MM.DD			
Beam	BS2	5	2015.MM.DD	2015.MM.DD			
Beam	BS3	5	2015.MM.DD	2015.MM.DD			
Beam	BS4	6	2015.MM.DD	2015.MM.DD			
Beam	B1CR	6	2015.MM.DD	2015.MM.DD			
Beam	B1D	6	2015.MM.DD	2015.MM.DD			
Beam	B1D	6	2015.MM.DD	2015.MM.DD			
Beam	BS1A	6	2015.MM.DD	2015.MM.DD			
…	…	…	…	…	…	…	…

Table B.8: Example of transportation schedule

Transportation schedule								
Product	Product ID	Product weight (kg.)	Transport Sequence	Transportation schedule		Transportation status		
				Plan	Actual	Loading	Delivery	Approval
Level 01								
Column	C1	120	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	120	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	120	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1A	129.6	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1B	129.6	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1C	139.2	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1D	139.2	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	139.2	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	139.2	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	139.2	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	139.2	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1F	129.6	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1G	129.6	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1H	129.6	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1I	129.6	2	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1J	129.6	2	2015.MM.DD	2015.MM.DD	✓	✓	
Beam	B1	312.48	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1A	298.56	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1B	298.56	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1CL	490.56	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1E	202.56	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B1X	402.48	3	2015.MM.DD	2015.MM.DD	✓		
Beam	B2	682.56	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2A	682.56	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B2B	682.56	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3	367.20	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3A	586.56	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B3X	878.88	4	2015.MM.DD	2015.MM.DD	✓		
Beam	B5	551.88	5	2015.MM.DD	2015.MM.DD			
Beam	B6	557.28	5	2015.MM.DD	2015.MM.DD			
Beam	BS1	150.66	5	2015.MM.DD	2015.MM.DD			
Beam	BS1B	289.44	5	2015.MM.DD	2015.MM.DD			
Beam	BS2	572.76	5	2015.MM.DD	2015.MM.DD			
Beam	BS3	205.20	5	2015.MM.DD	2015.MM.DD			
Beam	BS4	317.52	6	2015.MM.DD	2015.MM.DD			
Beam	B1CR	261.36	6	2015.MM.DD	2015.MM.DD			
Beam	B1D	490.56	6	2015.MM.DD	2015.MM.DD			
Beam	B1D	169.92	6	2015.MM.DD	2015.MM.DD			
Beam	BS1A	169.92	6	2015.MM.DD	2015.MM.DD			
…	…	…	…	…	…	…	…	…

Table B.9: Example of erection schedule

Erection schedule								
Product	Product ID	Product weight (kg.)	Erection Sequence	**Erection schedule**		**Erection status**		
				Plan	Actual	Erecting	Finishing	Approval
Level 01								
Column	C1	120	1	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	120	2	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1	120	3	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1A	129.6	4	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1B	129.6	5	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1C	139.2	6	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1D	139.2	7	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	139.2	8	2015.MM.DD	2015.MM.DD	✓	✓	✓
Column	C1E	139.2	9	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	139.2	10	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1E	139.2	11	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1F	129.6	12	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1G	129.6	13	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1H	129.6	14	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1I	129.6	15	2015.MM.DD	2015.MM.DD	✓	✓	
Column	C1J	129.6	16	2015.MM.DD	2015.MM.DD	✓	✓	
Beam	B1	312.48	17	2015.MM.DD	2015.MM.DD	✓		
Beam	B1A	298.56	18	2015.MM.DD	2015.MM.DD	✓		
Beam	B1B	298.56	19	2015.MM.DD	2015.MM.DD	✓		
Beam	B1CL	490.56	20	2015.MM.DD	2015.MM.DD	✓		
Beam	B1E	202.56	21	2015.MM.DD	2015.MM.DD	✓		
Beam	B1X	402.48	22	2015.MM.DD	2015.MM.DD	✓		
Beam	B2	682.56	23	2015.MM.DD	2015.MM.DD	✓		
Beam	B2A	682.56	24	2015.MM.DD	2015.MM.DD	✓		
Beam	B2B	682.56	25	2015.MM.DD	2015.MM.DD	✓		
Beam	B3	367.20	26	2015.MM.DD	2015.MM.DD	✓		
Beam	B3A	586.56	27	2015.MM.DD	2015.MM.DD	✓		
Beam	B3X	878.88	28	2015.MM.DD	2015.MM.DD	✓		
Beam	B5	551.88	29	2015.MM.DD	2015.MM.DD			
Beam	B6	557.28	30	2015.MM.DD	2015.MM.DD			
Beam	BS1	150.66	31	2015.MM.DD	2015.MM.DD			
Beam	BS1B	289.44	32	2015.MM.DD	2015.MM.DD			
Beam	BS2	572.76	33	2015.MM.DD	2015.MM.DD			
Beam	BS3	205.20	34	2015.MM.DD	2015.MM.DD			
Beam	BS4	317.52	35	2015.MM.DD	2015.MM.DD			
Beam	B1CR	261.36	36	2015.MM.DD	2015.MM.DD			
Beam	B1D	490.56	37	2015.MM.DD	2015.MM.DD			
Beam	B1D	169.92	38	2015.MM.DD	2015.MM.DD			
Beam	BS1A	169.92	39	2015.MM.DD	2015.MM.DD			
…	…	…	…	…	…	…	…	…

Table B.10: Example of production checklist

	Production checklist								
	Preparation					**Production**			
Product ID	Cleaning	Mold assembly	Reinforcement placement	Embedded parts placement	1st approval	1st casting	2nd casting	Surface finishing	2nd approval
Level 01									
C1	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1A	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1B	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1C	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1D	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1E	✓	✓	✓	✓	✓	✓	✓	✓	✓
C1E	✓	✓	✓	✓	✓	✓			
C1E	✓	✓	✓	✓	✓	✓			
C1E	✓	✓	✓	✓	✓	✓			
C1F	✓	✓	✓	✓	✓	✓			
C1G	✓	✓	✓	✓	✓	✓			
C1H	✓	✓	✓	✓	✓	✓			
C1I	✓	✓	✓	✓	✓	✓			
C1J	✓	✓	✓	✓	✓	✓			
B1	✓	✓	✓	✓					
B1A	✓	✓	✓	✓					
B1B	✓	✓	✓	✓					
B1CL	✓	✓	✓	✓					
B1E	✓	✓	✓	✓					
B1X	✓	✓	✓	✓					
B2	✓	✓	✓	✓					
B2A	✓	✓	✓	✓					
B2B									
B3									
B3A									
B3X									
B5									
B6									
BS1									
BS1B									
BS2									
BS3									
BS4									
B1CR									
B1D									
…	…	…	…	…	…	…	…	…	…

VITA

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Wongwisuth is currently working to earn a license of professional civil engineer. His research interest focuses on construction management, building information modeling, and supply chain management.