แบบจำลองการประเมินความสามารถในการก่อสร้างสำหรับงานก่อสร้างอาคารในประเทศกัมพูชา

นายเฮง ลี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาวิศวกรรมโยธา ภาควิชาวิศวกรรมโยธา
คณะวิศวกรรมศาสตร์ จุฬาลงกรณ์มหาวิทยาลัย
ปีการศึกษา 2557

BUILDABILITY ASSESSMENT MODEL FOR BUILDING CONSTRUCTION IN COMBODIA

Mr. Heng Ly

A Thesis Submitted in Partial Fulfillment of the Requirements
for the Degree of Master of Engineering Program in Civil Engineering
Department of Civil Engineering
Faculty of Engineering
Chulalongkorn University
Academic Year 2014

Thesis Title	BUILDABILITY ASSESSMENT MODEL FOR BUILDING CONSTRUCTION IN COMBODIA
By	Mr. Heng Ly
Field of Study	Civil Engineering
Thesis Advisor	Associate Professor Tanit Tongthong, Ph.D.
Thesis Co-Advisor	Assistant Professor Vachara Peansupap, Ph.D.

Accepted by the Faculty of Engineering, Chulalongkorn University in Partial Fulfillment of the Requirements for the Master's Degree

....Dean of the Faculty of Engineering
(Professor Bundhit Eua-arporn, Ph.D.)

THESIS COMMITTEE

....Chairman
(Assistant Professor Noppadon Jokkaw, Ph.D.)

....Thesis Advisor
(Associate Professor Tanit Tongthong, Ph.D.)

....Thesis Co-Advisor
(Assistant Professor Vachara Peansupap, Ph.D.)

....External Examiner
(Assistant Professor Kongkoon Tochaiwat, Ph.D.)

เฮง ลี : แบบจำลองการประเมินความสามารถในการก่อสร้างสำหรับงานก่อสร้างอาคารในประเทศกัมพูชา (BUILDABILITY ASSESSMENT MODEL FOR BUILDING CONSTRUCTION IN COMBODIA) อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ. ธนิต ธงทอง, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม: ผศ. วัชระ เพียรสุภาพ, 129 หน้า.

ความสามารถในการก่อสร้างเกี่ยวข้องกับการผสมผสานความรู้ด้านต่างๆของการก่อสร้างในช่วงการออกแบบเพื่อเพิ่มความสามารถในการก่อสร้างได้อย่างสะดวก ในขณะที่สามารถตอบสนองต่อความต้องการของเจ้าของงานได้เช่นกัน การขาดความสามารถในการก่อสร้างในช่วงออกแบบสามารถส่งผลให้เกิดการออกแบบซ้ำ การทำงานที่ล่าช้า ค่าใช้จ่ายที่เพิ่มขึ้น และการเปลี่ยนแปลงสัญญา เนื่องจากความแตกต่างในสภาพการทำงาน วิธีการทำงาน วัตถุดิบ เครื่องมือ และประสบการณ์ที่มีอยู่ ทำให้ความสามารถในการก่อสร้างมีความผันแปรไปตามแต่ละประเทศ ดังนั้นแบบจำลองสำหรับประเมินความสามารถในการก่อสร้างในช่วงการออกแบบขั้นต้นจึงจำเป็นต้องพัฒนา โดยใช้ปัจจัยที่มีอยู่ภายในท้องที่นั้นๆ เป็นหลัก

งานวิจัยนี้ถูกแบ่งออกเป็นสองส่วน ในส่วนแรกมีจุดมุ่งหมายเพื่อประเมินความสำคัญของปัจจัยต่างๆที่ส่งผลต่อความสมารถในการก่อสร้างของแบบก่อสร้างในประเทศกัมพูชา แบบสอบถามที่ใช้มาตราของไลเกิร์ตแบบห้าคะแนนถูกแจกจ่ายไปยังผู้จัดการโครงการและวิศวกรสนามของผู้รับเหมาในประเทศกัมพูชา การวิเคราะห์ค่าเฉลี่ยของกลุ่มตัวอย่างหนึ่งกลุ่ม (One-sample *t*-test) แสดงให้เห็นว่ามี ๑๒ ปัจจัยสำคัญที่ส่งผลต่อความสามารถในการก่อสร้าง ปัจจัยที่มีความสำคัญสูงสุด ๕ อันดับแรกได้แก่ (๑) การปรับแบบก่อสร้างให้เข้ากับมาตรฐาน (๒) เอกสารแบบก่อสร้างที่แล้วเสร็จ (๓) ข้อจำกัดที่ชัดเจน (๔) ความต้องการความสามารถของแรงงาน และ (๕) แบบก่อสร้างที่เหมาะสมกับเงื่อนไขสถานที่ก่อสร้าง ลำดับโดยรวมและลำดับในปัจจัยแต่ละประเภทให้ข้อมูลที่เป็นประโยชน์แก่ผู้ออกแบบทำให้สามารถเพิ่มความสามารถในการก่อสร้างของแบบก่อสร้างได้ ปัจจัยที่สำคัญในงานวิจัยนี้ถูกใช้ในการพัฒนาแบบจำลองสำหรับการประเมินความสามารถในการก่อสร้างของงานก่อสร้างอาคารในประเทศกัมพูชาในขั้นต่อไป

ในส่วนที่สองให้ความสำคัญกับขั้นตอนการพัฒนาแบบจำลองสำหรับประเมินความสามารถในการก่อสร้างในช่วงของการออกแบบงานอาคาร แบบจำลองถูกสร้างขึ้นจากการตัดสินใจด้วยวิธีวิเคราะห์เชิงลำดับขั้น (Analytic Hierarchy Process) งานวิจัยในขั้นนี้ถูกแบ่งออกเป็น ๒ ส่วน ในส่วนที่หนึ่ง แบบสอบถามที่มีการเตรียมคำถามไว้ล่วงหน้าถูกจัดทำขึ้นให้ผู้รับเหมางานอาคารสูงปานกลางและอาคารสูงเพื่อให้ได้ค่าถ่วงน้ำหนักของปัจจัยที่ส่งผลต่อความสามารถในการก่อสร้าง ความคิดเห็นของผู้รับเหมาถูกรวบรวมโดยใช้ค่าเฉลี่ยเรขาคณิตตามดุลยพินิจ (Geometric mean on judgments) ในการตัดสินใจแบบกลุ่มของวิธีวิเคราะห์เชิงลำดับขั้น จากนั้นใช้วิธีการวิเคราะห์ระหว่างเหตุการณ์ (Cross-case analysis) โดยการสัมภาษณ์แบบมีการวางแผน (Structured interview) ถูกจัดทำขึ้นเพื่อให้ได้ซึ่งเกณฑ์ย่อยของปัจจัยที่ส่งผลต่อความสามารถในการก่อสร้างและการทำงานจริงในปัจจุบัน แบบก่อสร้างที่ถูกออกแบบเพื่อวัตถุดิบท้องถิ่น พบว่าเป็นปัจจัยที่มีความสำคัญมากที่สุดต่อความสามารถในการก่อสร้าง ตามมาด้วยแบบก่อสร้างที่ถูกออกแบบเพื่อสนับสนุนผังสถานที่ก่อสร้างและเอกสารการออกแบบ ปัจจัยที่มีความสำคัญต่อความสามารถในการก่อสร้างสูงสุดภายใต้หมวดหมู่ต่างๆ ได้แก่ แบบก่อสร้างที่สนับสนุนการขนส่งวัตถุดิบและแรงงาน ความต้องการความสามารถของแรงงาน และเอกสารแบบก่อสร้างที่แล้วเสร็จ แบบจำลองนี้ได้รับการตรวจสอบโดยการประยุกต์ใช้กับงานก่อสร้างอาคารจำนวน ๑๑ โครงการในประเทศกัมพูชา แบบจำลองนี้สามารถทำหน้าที่เป็นกรอบความคิดสำหรับการประเมินความสามารถในการก่อสร้างของงานก่อสร้างอาคารโดยกลุ่มผู้ออกแบบเพื่อให้สามารถเกิดการพัฒนาปรับปรุงแบบที่จำเป็นต่อไป

ภาควิชา	วิศวกรรมโยธา	ลายมือชื่อนิสิต	....
สาขาวิชา	วิศวกรรมโยธา	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....
ปีการศึกษา	2557	ลายมือชื่อ อ.ที่ปรึกษาร่วม	....

5570581621 : MAJOR CIVIL ENGINEERING
KEYWORDS: BUILDABILITY / ASSESSMENT MODEL / BUILDING DESIGN / BUILDING CONSTRUCTION / CAMBODIA

HENG LY: BUILDABILITY ASSESSMENT MODEL FOR BUILDING CONSTRUCTION IN COMBODIA. ADVISOR: ASSOC. PROF. TANIT TONGTHONG, Ph.D., CO-ADVISOR: ASST. PROF. VACHARA PEANSUPAP, Ph.D., 129 pp.

Buildability refers to the integration of construction knowledge during the design stage to enhance the ease of construction while meeting all requirements of the owner/client. Lack of buildability in designs could result in design reworks, low site productivity, costs increase, and contract changes. Due to differences in site conditions, construction techniques, materials, equipment and experiences available, the buildability factors vary from countries to countries. Therefore, a model to comprehensively evaluate the buildability of building designs based on localized buildability factors at early phase of design is needed.

The research is divided into two main parts. The first part aims to evaluate the importance level of buildability factors of building designs in Cambodia. The questionnaires using five-point Likert scale were distributed to project managers and site engineers of contractors in Cambodia. The analysis of One-sample *t*-test showed that there were 12 important factors that affected the buildability. The top 5 important factors associated with buildability were: (1) standardization of designs; (2) completion of design documents; (3) clarity of specifications; (4) requirement of labor skill; and (5) design to suit site conditions. The ranking of the factors and factor categories provides useful information for designers to improve buildability of their designs. The important factors of this research were then used for the development of buildability assessment model for building construction projects in Cambodia.

The second part focuses on the development process of a model to assess the buildability of building design. The model was based on an Analytic Hierarchy Process (AHP) model. This part of research was divided into two main steps. First, structured questionnaires were conducted with mid- and high-rise building contractors to obtain the weights of buildability factors. Their opinions were aggregated by the geometric mean on judgments in AHP group decision. Then the subcriteria to evaluate the buildability factors and the current practices of designs were collected by cross-case analysis of structured interviews. Design for available resources was found to be the most important category of buildability followed by design to support site layout and design documents. The most important buildability factor under each category was design to support transportation of materials and labors, requirement of labor skill, and completion of design documents. This model was validated by applying 11 building projects in Cambodia. This model can serve as a framework to assess the buildability of a building design by the design team so that necessary improvements can be made before construction.

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

ACKNOWLEDGEMENTS

I would like to take this opportunity to extend my heartfelt thanks to my chief adviser, Assoc. Prof. Tanit Tongthong, for giving critical advice and guidance during my study of this Master's Degree program. Special thanks are extended to my co-adviser, Asst. Prof. Vachara Peansupap, for his thoughtful suggestions for conducting the research and conveying ideas. I would like to thank the chairman of the committee, Asst. Prof. Noppadon Jokkaw, and external committee, Asst. Prof. Kongkoon Tochaiwat, for their challenging questions, insightful comments and suggestions on reviewing the thesis.

I am grateful for the respondents of the questionnaire surveys of this research, especially my seniors graduated from Chulalongkorn University, for sharing their experience, comments and insights throughout the data collection process. My thanks also go to all lectures and teachers who have taught me.

I gratefully acknowledge the financial support of scholarship and research budget from ASEAN University Network/ Southeast Asia Engineering Education Development Network (AUN/SEED-Net) for my study at Chulalongkorn University.

Finally, I would like to express my profound thanks to my family for being understanding and supportive during my living and studying. I also would like to thank all my friends for helping and sharing their time with me, without them I would not be able to have such a great time here.

CONTENTS

Page

Page

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER I
INTRODUCTION

1.1 Introduction

As the design and construction of projects become increasingly complex, more attention is given to the exchanges of knowledge during the preconstruction phase in order to develop the best design solution (Uhlik and Lores, 1998). Buildability is the concept of using construction knowledge in design (BCA, 2013), so as to eliminate potential construction problems caused by the design. Buildability of a design could be improved by implementing the buildability principles and guidelines by the designers, using the computerized systems to assess the design details, manually reviewing the designs, or assessing the buildability of the designs quantitatively.

There is no general consensus on the best method to improve the buildability, nor on the impacts and the root causes of the buildability problems. This research is interested in quantitative assessment of buildability because it can be used to benchmark and improve the buildability of the designs based on the opinions of a group of construction experts.

Currently, there are several quantitative buildability assessment models, such as the Buildable Design Appraisal System (BDAS) enforced by the government of Singapore, the Buildability Assessment Model (BAM) and Scheme Design Buildability Assessment Model (SDBAM) developed in Hong Kong, and other models in Thailand and Malaysia.

1.2 Problem Statements

Insufficient buildability in designs could result in design reworks, changes in contract, problems with scheduling and cost, claims and disputes during the construction (Arditi et al., 2002). The most important root cause of the buildability problems is the lack of design review (Mydin et al., 2011). A model to evaluate the buildability of a design is an important tool to benchmark and improve the buildability.

There are several models using different methods to assess the buildability of a design. Nevertheless, the focus and the factors used to develop these models were based on the specific environment of each country. The Buildable Design Appraisal System (BDAS) uses a labor saving index as the assessment criterion. The Buildability Assessment Model (BAM) considers labor and effect of site conditions as the main assessment criteria. Both models promote the building components that use advanced construction technologies, e.g. precast and prefabrication. These models also use types of building components as the alternatives instead of the design details to evaluate the buildability.

The building construction industry in Cambodia is less developed than those in its neighboring countries, such as Thailand and Vietnam. There are many low-paid and low-skilled labors available. The building construction technologies are less advanced. Most of the construction materials are imported and the choices of the materials are limited in the local markets. Construction stakeholders are segregated due to the use of Design-Bid-Build as the main project delivery method. The local designers and the local contractors still have less experience. They are learning the modern construction technologies and the management practices. Due to the differences of the construction industries, a buildability assessment model tailored to suit the Cambodian construction industry is needed.

1.3 Objectives of Research

This research aims to identify the important factors to evaluate the buildability of building designs and to develop a model to evaluate the buildability of building designs in Cambodia.

1.4 Scope of Research

This research focused on collecting and refining the opinions of the contractors in the Cambodian construction industry about buildable designs and transforming their opinions into a buildability evaluation model. The target respondents of this research are contractors of private medium- and high-rise commercial and residential building projects in Phnom Penh city. The city was selected because it is the capital city of Cambodia, the centre of politics and commerce, where the headquarters of many construction companies are located.

The most quoted definition of high-rise building is given by (Emporis) (2009) in ESN 18727 which defines a high-rise building as a multi-story structure between 35-100 meters tall, or a building of unknown height from 12 – 39 floors. The same organization also defines the low-rise building as an enclosed structure below 35 meters (Emporis) (2009). However, this organization does not differentiate between the low and mid-rise building. In the paper of Erberik (2008) which focused on the seismic fragility assessment of typical low-rise and mid-rise reinforced concrete building in Turkey, he defined the building with 2 and 3 storeys as low-rise, and the building with 4 to 6 storeys as mid-rise. In Thailand, a high-rise buildings was defined as a structure higher than 23 meters in the Building Control Act (OCST, 1979).

In this research, differentiation between mid-rise and low-rise building was made. A low-rise building refers to a building with 1 to 3 storeys or less than 12 meters high, while a mid-rise building is defined as a building with 4 to 11 storeys or from 12 to 35 meters high, and a high-rise building is a building with 12 to 40 storeys of from 35 to 100 meters high.

1.5 Research Procedures

The first step of this research was to review the literature about the buildability concepts, benefits, and implementations. A list of factors that affect the buildability was refined from literature reviews and verified by the construction experts for the completeness and appropriateness in the pilot survey by unstructured interviews.

Then the questionnaire for main survey was developed using the Analytical Hierarchy Process (AHP) as a framework. In this structured questionnaire, the respondents were required to make pairwise comparisons in two levels. The reasons of scoring were also investigated concurrently. The respondents were encouraged to share their opinions and suggestions on the questionnaire.

The data from the questionnaire were analyzed and translated into a buildability assessment model that was applicable to common mid- and high-rise buildings in Cambodia.

Finally, this model was validated by scoring buildability for actual building designs and in-depth interviews with construction experts in Cambodia. Their opinions about the validity, the applicability, and the convenience of using the model were summarized for the conclusion of the study.

1.6 Expected Output and Benefits

The first output of this research is a list of prioritized factors that affect the buildability. This list is the input to develop the evaluation model and to formulate appropriate strategies to improve the buildability. These factors could also raise the awareness of the architects and the design engineers about the buildability throughout the design phase.

The second output is a model to evaluate buildability of a building design based on the buildability factors. It is a useful tool for the engineers and the designers to evaluate the buildability of a design in the early stages of the project development. The knowledge of the subcriteria to evaluate each buildability is also extracted to facilitate the use of the model. The goal of this model is not to limit the creativity of the designers, but to facilitate the building construction process to achieve higher productivity and quality through the designs with higher buildability.

1.7 Research Outline

Chapter 1 introduces the definitions and the studies of buildability in different countries. The importance and the scope of this research were discussed. The focus of this study was on the development of buildability assessment model for building designs in Cambodia. This study would provide a comprehensive understanding about the factors that affect the buildability and the current practices of building designs.

Chapter 2 illustrates the origin and the development of the buildability studies in different countries. Three buildability assessment models were presented. The barriers, the benefits, and the factors that affect the buildability implementation were identified. Finally, the main approaches for buildability improvement were discussed.

Chapter 3 explains about the methodology to obtain the expected output. The buildability concepts and the factors that affect the buildability were summarized from the literature. A questionnaire for the pilot survey was made. In the pilot survey, the perceptions of the experts concerning the buildability, the clarity and the comprehensiveness of the draft questionnaire were interviewed. The main questionnaire in form of AHP was refined and distributed to the target respondents for large-scale data collection. The arguments of the scoring in the main questionnaire were also recorded. The data were analyzed and transformed into a buildability evaluation model. Scoring of buildability for actual building projects and in-depth interviews with construction experts were conducted to validate the model.

Chapter 4 describes about the process to identify the importance factors that affect the buildability and the results of identification. The buildability factors collected from literature reviews were evaluated by the respondents using 5-point Likert scale. The importance level of each buildability factor was tested by one-sample *t*-test. The internal consistency of the test and the concordance of the answers were also analyzed.

Chapter 5 elaborates the development process of the buildability evaluation model. There were three levels of the AHP model, namely the goal, the criteria, and the buildability factors. The subcriteria and the current practices of the subcriteria were not included in the model as they will make the model too complicated, but they were described to facilitate the users to evaluate more objectively. Moreover, Liberatore 5-point rating scale was used instead of normal AHP model for the pairwise comparisons among the alternatives to simplify the evaluation process.

Chapter 6 discusses about the validation process and the validation results of the buildability assessment model. The technical validity of the model was tested through the scorings of actual construction projects and the interviews with respondents. The divergence of the technical validity was also examined. The dynamic validity of the model was also discussed.

Chapter 7 summarizes the main findings of this research and illustrates the contributions of this research on the improvement of the buildability of building designs. The limitations of this model were explained. Some areas of improvements and further research were suggested in the last section.

CHAPTER II
LITERATURE REVIEWS

2.1 Buildability Studies

The conventional construction project procurement using the design-bid-build method has segregated the design phrase from the construction phase. This practice prevents effective communication between the designers and the contractors, which in turn increased the potential construction problems caused by defective designs. The report of Emmerson (1962) submitted to the U.K. government drew specific attentions to the effect on the inadequacies of communication and coordination on many problems experienced in the construction industry. Another report (Banwell, 1964) suggested that the specialized knowledge and techniques of the contractors must be considered in the designs. A subsequent study ((EDC), 1967) reported that the recommendations in the Banwell report were not implemented within the construction industry, flexible approaches to traditional procedures and new initiatives were necessary to change the industry. The Wood Reports ((NEDO), 1975) pointed out that some improvements had been made to integrate the design and the construction process after the Emmerson and Banwell reports. However, in order to promote the input of construction knowledge in designs, more efforts should be made to increase the level of awareness of the problems and the design measures. These reports had inspired researchers in various countries to investigate the integration of the design and the construction processes in the project development.

2.2 Development of Buildability and Constructability Concepts

This section reviews the research results concerning buildability and constructability in 5 countries: the United Kingdoms, the United States, Australia, Singapore, and Hong Kong.

2.2.1 Buildability Consideration in the United Kingdom

After the report of Emmerson, Banwell and NEDO, the Construction Industry Research and Information Association (CIRIA, 1983) initiated a major research to investigate the principle problems of construction practice. The report of CIRIA in 1983 defined buildability as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building". The same report also represented seven categories of buildability principles: to carry out thorough investigation and design, plan for essential site production requirements, plan for a practical sequence of operations and early disclosure, plan for simplicity of assembly and logical trade sequences, detail for maximum repetition and standardization, detail for achievable tolerance, and specify robust and suitable materials. The study of CIRIA raised the awareness of the concepts and the principles of buildability.

Griffith (1984a) proposed the involvement of construction expertise in the early design stage to improve the buildability through contractual arrangement. Griffith (1984b) further recognized the influence of the managerial aspects of increasing productivity, achieving better buildability and overcoming inadequate design. Winch and Carr (2001) also referred the inadequate input of the contractors into designs as one of the main causes of low productivity in the UK. Egan (1998) further pointed out that integrate the process and the team around the product as one of the key drivers to change the construction industry. As he noted:

> *'The Task Force has looked for this concept in construction and see the industry typically dealing with the project process as a series of sequential and largely separate operations undertaken by individual designers, constructors, and suppliers who have no stake in the long term success of the product and no commitment to it. Changing this culture is fundamental to increasing efficiency and quality in construction.'*

2.2.2 Constructability Study in the United States

In the U.S., the term constructability is used instead of buildability to refer to a broader range of concepts. In the early 1980s, concerns to provide the highest degree of quality and cost effectiveness for projects of the American construction industry led to the establishment of Construction Industry Cost Effectiveness Project (CICE) Task Force. Its report (1982) concluded that 'the benefits to be gained from good constructability throughout the building process are about 10 to 20 times the cost of achieving it'. Subsequently, the Business Roundtable initiated the establishment of the Construction Industry Institute (CII) in 1983, based at the University of Texas in Austin, to conduct the research on new management methods and techniques to improve the construction industry. Hence, constructability was defined as "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve the overall project objectives" ((CII), 1986).

In (1987), CII published the constructability guidelines in the form of Constructability Concepts File covering 14 concepts, 6 for consideration during conceptual planning, 7 for consideration during the design, engineering and procurement stages, and 1 concept for consideration during site operations. The guidelines were updated in 1997 to cover 17 concepts, 8 for conceptual planning, 8 for design and procurement, and 1 for field operation ((CII), 1997).

Conceptual Planning Concepts

1. Detail of the constructability program should be an integral part of project execution plan
2. Project planning involves construction knowledge and experience
3. Early construction involvement is considered in development of contracting strategy
4. Project schedules are construction-sensitive
5. Basic design approaches consider major construction methods
6. Site layout promotes efficient construction
7. Project team participants responsible for constructability are identified early on
8. Advanced information technologies are applied throughout the project

Design and Procurement Concepts

1. Design and procurement schedules are construction-sensitive
2. Design are configured to enable efficient construction
3. Design elements are standardized
4. Construction efficiency is considered in specification development
5. Module/preassembly designs are prepared to facilitate fabrication, transportation, and installation
6. Design promotes construction accessibility of personnel, material, and equipment
7. Design facilitates construction under adverse weather conditions
8. Design and construction sequencing should facilitate system turnover and start-up

Field Operations Concept

1. Constructability is enhanced when innovative construction methods are used

Figure 2.1 Constructability Guidelines ((CII), 1997)

The implementation of these constructability guidelines exerts greater attention on overall optimization of schedule and cost at the early phases of a project and the choice of construction methods and technologies. Since then, constructability has gained acceptance throughout the industry in the U.S., but the constructability techniques were varied (Pocock et al., 2006).

2.2.3 Buildability and Constructability in Australia

In Australia, contribution of constructability was reviewed within a project management setting (Hon et al., 1989). McGeorge et al. (1992) suggested that constructability should not focus only on the design and construction relationship, but on total building process, and constructability could contribute throughout the project life cycle. Between 1991 and 1993, the CII Australia collaborated with CII in the U.S. to develop a Constructability Principles File appropriate in the Australian context (Australia, 1993). Constructability is defined as "a system for achieving optimum integration of construction knowledge in the building process and balancing the various projects and environmental constraints to achieve maximization of project goals and building performance" (Australia, 1993). The constructability concept was developed in 12 principles to apply in the project (Griffith and Sidwell, 1997).

Integration
Constructability must be made an integral part of the project plan.

Construction knowledge
Project planning must actively involve construction knowledge and experience.

Team skills
The experience, skills and composition of the project team must be appropriate for the project.

Corporate objectives
Constructability is enhanced when the project team gains an understanding of the client's corporate and project objectives.

Available resources
The technology of the design solution must be matched with the skills and resources available.

External factors
The overall program for the project must be realistic and/or program of the project.

Program
The overall program for the project must be realistic and construction-sensitive, and have the commitment of the project team.

Construction methodology
The project design must consider construction methodology.

Accessibility
Constructability will be enhanced if construction accessibility is considered in the design and construction stages of the project.

Specifications
Project constructability is enhanced when construction efficiency is considered in specification developments.

Construction innovation
The use of innovative techniques during construction will enhance constructability.

Feedback
Constructability can be enhanced on similar future projects if a post-construction analysis is undertaken by the project team.

Figure 2.2 CIIA Principles of Constructability (Griffith and Sidwell, 1997)

In the later studies, the constructability concept was extended to include Operation and Maintenance (O&M) issues to improve the effectiveness and the efficiency of infrastructure projects (Saghatforoush et al., 2011). An extended constructability model incorporating O&M was proposed to integrate these concepts in order to maximize the benefits of their implementations (Saghatforoush et al., 2012).

2.2.4 The Buildable Design Appraisal System in Singapore

According to the report of Construction Industry Development Board (CIDB, 1989), the unit construction cost of luxury apartments, offices and hotels in Perth, Australia was only 5-10% higher than those of Singapore, although the basic building materials in Perth were 60% and labor wages were 400-500% higher than those in Singapore. In 1991, CIDB appointed a construction productivity task force to investigate the problems of construction productivity (Poh and Chen, 1998). This task force identified buildability as a main potential for improving performance (CIDB, 1992). Later, a buildable design appraisal system (BDAS) was developed and published (CIDB, 1993). The system was modelled after Takenaka's (a major Japanese contractor) system. In 2001, all building designs in Singapore were required to have a minimum Buildability Score under the Building Control Act. The Buildability Score for different types of buildings was calculated based on BDAS in the Code of Practice on Buildable Design (BCA, 2000). This is the first Code that sets out the minimum quantitative requirements of buildability.

There were several amendments and revisions made to the code. In 2011, the Code of Practice on Buildable Design was renamed as the Code of Practice on Buildability to reflect the development of buildability concepts beyond the design phase. The most recent update was made in 2013.

The first part of the new code, Buildable Design Appraisal System (BDAS), measures the potential impact of a building design on the usage of labor. The appraisal system results in a 'Buildable Design Score' of building design. A design with a higher Buildable Design Score will result in more efficient labor usage in the construction and therefore higher labor productivity. The 3S principles to achieve a buildable design are Standardization, Simplicity and Single integrated elements. The Buildable Design Score for a project is calculated by summing the Buildable Design Score of structural systems (maximum 50 points), wall systems (maximum 45 points), other buildable design features (maximum 30 points), and bonus points. The maximum Buildable Design Score achievable for a project is 125 points. The computation of Buildable Design Score is shown in the Figure 2.3 (BCA, 2013).

The second part of the new code, Constructability Appraisal System (CAS), measures the potential impact of downstream construction methods and technologies on the productivity at site. The CAS results in a 'Constructability Score' of the building works. A project with higher Constructability Score will result in the use of more labor efficient construction methods and technologies, and therefore improve the site labor productivity. The Constructability Score for a project is calculated by summing the Constructability Score from structural works (maximum 60 points), architectural, mechanical, electrical and plumbing (AMEP) works (maximum 50 points), and good practices (maximum 10 points). The computation of Constructability Score is shown in the Figure 2.4 (BCA, 2013).

Buildable Design (BD) Score of Building	=	Buildable Design Score of Structural System (including Roof System) + Buildable Design Score of Wall System + Buildable Design Score of Other Buildable Design Features
BDScore	=	$45[\sum(A_s x S_s)]$ + Structural Bonus points + $40[\sum (L_w x S_w)]$ + C + N + Bonus points
where A_s	=	A_{sa} / A_{st}
L_w	=	L_{wa} / L_{wt}
A_s	=	Percentage of total floor area using a particular structural system
A_{st}	=	Total floor area which includes roof (projected area) and basement area
A_{sa}	=	Floor area using a particular structural system
Lw	=	Percentage of total external & internal wall length using a particular wall system
Lwt	=	Total external & internal wall length, excluding the length of external basement wall for earth retaining purpose.
Lwa	=	External & internal wall length using a particular wall system
Ss	=	Labour saving index for structural system (Table 1)
Structural Bonus points	=	Bonus points for the use of recommended precast joints, mechanical connections for precast joints, high strength concrete, self-compacting concrete and diaphragm wall (Table 1)
Sw	=	Labour saving index for external & internal wall system (Table 2)
C	=	Buildable Design Score for simple design (Table 2)
N	=	Buildable Design Score for other buildable design features (Table 3)
Bonus points	=	Bonus points for the use of single integrated components, industry standard building components/design parameters, dry construction and labor-saving MEP systems (Table 3)

Figure 2.3 Buildable Design Score Formula of BDSA in Singapore (BCA, 2013)

Constructability Score of Building Works	=	Constructability Score of Structural System + Constructability Score of AMEP System + Constructability Score of Good Industry Practices

Figure 2.4 Constructability Score Formula of BDSA in Singapore (BCA, 2013)

The higher Buildable Design Score as calculated based on BDAS was found to be associated with improved site productivity, shortened project time and reduced construction cost concomitant with manpower saving (Lam, 2002, Low and Abeyegoonasekera, 2001, Poh and Chen, 1998, Wong and Lam, 2008). On the other hand, the effects of CAS are not yet determined by case study.

2.2.5 The Buildability Assessment Model (BAM) in Hong Kong

The report of the Construction Industry Review Committee (CIRC) in 2001 highlighted that little emphasis was placed on the buildability and the life-cycle cost considerations during the design development in Hong Kong (CIRC, 2001). It also suggested that greater emphasis on the buildability of designs at the start of the project would result in wider adoption of cost-saving and labor-saving construction technologies, and minimize material wastage at the same time. Detailed planning at the start of a project and a design that takes full account of practical issues arising from other downstream activities lay a firm foundation for smooth project delivery (CIRC, 2001).

In view of the similarity in the construction environment and the success in implementing the BDAS in Singapore, a model with similar rationale called Buildability Assessment Model (BAM) was developed for the adoption in Hong Kong (Wong, 2007). In this model, the buildability of a building design is assessed based on 6 design components: Structural Frame Systems, Slab Systems, Envelope Systems and Roof Systems adopted for the building carcass as well as Other Building Features (comprising Internal Wall Systems, Finishing Systems, Building Services Aspects and Building Features), and Site Specific Factors. The Buildability Score is the summation of the sub-scores of the 6 design components described above. The sub-scores of the Structural Frame Systems, Slab Systems, Envelope Systems, Roof Systems, and 2 Other Buildable Features (Internal Wall Systems and Finishing Systems) are calculated according to the proportional volume or area coverage and the related Buildable Indexes. For Building Service Aspects, Building Features, and Site Specific Factors, the sub-scores are based on the physical coverage of individual design elements and the corresponding Buildability Indexes of the elements. The Computation of Buildability Score is shown in Figure 2.5 (Wong, 2007).

Buildability Score (BScore) of a project =

23$\sum(V_S \times BI_S)$	+ **14** $\sum(A_l \times BI_l)$	+ **19** $\sum(A_e \times BI_e)$	+ **10** $\sum(A_r \times BI_r)$	+ **3** $\sum(A_w \times BI_w)$
Construction Systems (Structural Frames)	Construction Systems (Slabs)	Construction Systems (Envelopes)	Construction Systems (Roofs)	Other Buildable Features (Internal Walls)

+ **2** $(BS_{finishing} / 100)$	+ **3** $\sum(BI_{bs} \times cov_{bs})$ / Sum of all BI_{bs}	+ **4** $\sum(BI_{bf} \times cov_{bf})$ / Sum of all BI_{bf}	+ **12** $\sum BI_{ss}$ / Sum of all applicable BI_{ss}	+ **10** Bonus (10 points max.)
Other Buildable Features (Finishing Systems*)	Other Buildable Features (Building Services Aspects)	Other Buildable Features (Building Features)	Site Specific Factors	Open score for other innovations of improving buildability

<u>Notes:</u>

* Buildability score for finishing systems adopted = $BS_{finishing}$ =

20 $\sum(A_{iw} \times BI_{iw})$	+ **20** $\Sigma(A_{if} \times BI_{if})$	+ **20** $\Sigma(A_{ic} \times BI_{ic})$	+ **30** $\Sigma(A_{ew} \times BI_{ew})$	+ **10** $\Sigma(A_{rc} \times BI_{rc})$
Finishing systems for Internal walls	Finishing systems for Internal floors	Finishing systems for Internal ceilings	Finishing systems for External walls	Finishing systems for Roof coverings

where V_s = Percentage of total volume of major structural components using a particular <u>structural frame</u> design
i.e. (Volume of major structural components using a particular structural frame design / Total volume of major structural components) x 100%

A_l = Percentage of total construction floor area using a particular <u>slab</u> design
i.e. (Construction floor area using a particular slab design / Total slab areas) x 100%

A_e = Percentage of total elevation area using a particular <u>envelope</u> design
i.e. (Elevation area using a particular envelope design / Total envelope areas) x 100%

A_r = Percentage of total plan area using a particular roof design
i.e. (Plan area using a particular roof design / Total roof plan areas) x 100%

A_w = Percentage of total elevation area using a particular <u>internal wall</u> design
i.e. (Elevation area using a particular internal wall design / Total internal wall areas) x100%

A_{iw} = Percentage of total elevation area applying a particular <u>finishing system</u> at <u>internal walls</u>
i.e. (Elevation area applying a particular finishing system at internal walls / Total finishing areas at internal walls) x 100%

A_{if}	=	Percentage of total construction floor area applying a particular finishing system at internal floors i.e. (Construction floor area applying a particular finishing system at internal floors / Total areas of internal floors) x 100%
A_{ic}	=	Percentage of total construction area applying a particular finishing system at internal ceilings i.e. (Construction area applying a particular finishing system at internal ceilings / Total areas of internal ceilings) x 100%
A_{ew}	=	Percentage of total elevation area applying a particular finishing system at external walls i.e. (Elevation area applying a particular finishing system at external walls / Total areas of external walls) x 100%
A_{rc}	=	Percentage of total plan area applying a particular finishing system at roof coverings i.e. (Plan area using a particular finishing system at roof coverings / Total plan areas at roof coverings) x 100%
BI_s	=	Buildability index for a particular structural frame design
BI_l	=	Buildability index for a particular slab design
BI_e	=	Buildability index for a particular envelope design
BI_r	=	Buildability index for a particular roof design
BI_w	=	Buildability index for a particular internal wall design
BI_{iw}	=	Buildability index for a particular finishing system at internal walls
BI_{if}	=	Buildability index for a particular finishing system at internal floors
BI_{ic}	=	Buildability index for a particular finishing system at internal ceilings
BI_{ew}	=	Buildability index for a particular finishing system at external walls
BI_{rc}	=	Buildability index for a particular roof covering system
BI_{bs}	=	Buildability index for a particular building services aspect
BI_{bf}	=	Buildability index for a particular building feature
BI_{ss}	=	Buildability index for a particular site specific factor
cov_{bs}	=	Percentage coverage for a particular building services aspect
cov_{bf}	=	Percentage coverage for a particular building feature
Sum of all BI_{bf}	=	Sum of all buildability indices of building features
Sum of all BI_{bs}	=	Sum of all buildability indices of building services aspects
Sum of all applicable BI_{ss}	=	Sum of all buildability indices of site specific factors applicable to the project

Figure 2.5 Buildability Score Formula of BAM in Hong Kong (Wong, 2007)

2.2.6 Scheme Design Buildability Assessment Model

Scheme Design Buildability Assessment Model (SDBAM) was a model developed after BAM based on its comments of feedback survey conducted in 2008 (Lam et al., 2012). The respondents reasoned that the clients and the design professionals were reluctant to modify a completed design to improve buildability considering the time and effort spent. SDBAM was therefore focusing on the assessment of buildability at early stage of design, which is the scheme design stage.

SDBAM and BAM shared the same framework of buildability assessment, the portion of Construction System was kept unchanged.

Construction Systems **69**$\sum$(A x BI)

Structural frames	$\boldsymbol{23}\sum(V_S \text{ x } BI_S)$
Slabs	$\boldsymbol{14}\sum(A_l \text{ x } BI_l)$
Envelopes	$\boldsymbol{19}\sum(A_e \text{ x } BI_e)$
Roof	$\boldsymbol{10}\sum(A_r \text{ x } BI_r)$
Internal Wall	$\boldsymbol{3}\sum(A_w \text{ x } BI_w)$

Buildable Features **21**{ $\sum$ [$Wtg_{(\%)}$ x BR x Match Coeff $_{(1 \text{ or } 0)}$] $_{Max = 1}$

Non-buildable Features + $\sum$[$Wtg_{(\%)}$ x NBR x Match Coeff $_{(1 \text{ or } 0)}$] $_{Max = -1}$**}**

Innovation of Improving Buildability **10** Bonus (10 points max.)

Total Buildability Score = **100 (max.)**

Note: Wtg (%) is the normalized relative weighting relevant to the design decision

A	=	Proportion using a particular construction system
V_s	=	Percentage of total volume of major structural components using a particular structural frame design i.e. (Volume of major structural components using a particular structural frame design / Total volume of major structural components) x 100%
A_l	=	Percentage of total construction floor area using a particular slab design i.e. (Construction floor area using a particular slab design / Total slab areas) x 100%
A_e	=	Percentage of total elevation area using a particular envelope design i.e. (Elevation area using a particular envelope design / Total envelope areas) x 100%
A_r	=	Percentage of total plan area using a particular $_{roof}$ design i.e. (Plan area using a particular roof design / Total roof plan areas) x 100%
A_w	=	Percentage of total elevation area using a particular internal wall design i.e. (Elevation area using a particular internal wall design / Total internal wall areas) x100%
BI	=	Buildability Index for the construction system
BI_s	=	Buildability index for a particular structural frame design
BI_l	=	Buildability index for a particular slab design
BI_e	=	Buildability index for a particular envelope design
BI_r	=	Buildability index for a particular roof design
BI_w	=	Buildability index for a particular internal wall design
BR	=	Buildable Rating (+ve)
NBR	=	Non-buildable Rating (-ve)

Figure 2.6 Scheme Design Buildability Assessment Model (Lam et al., 2012)

In BAM, an accurate assessment could be carried out on a full design, but for SDAM, the assessment would be based on the estimation of the designers from outline drawings. The other components of the BAM, except bonus score for innovation, were replaced by buildable and non-buildable features in the SDBAM. There were 49 buildable features and 73 non-buildable features listed in the model. Each buildable feature had the rating from +1 to +3, and each non-buildable feature was rated from -1 to -3, with the match coefficient “1” or “0”.

By applying the normalization on Relative Weightings in percentage, the sum of the products of the buildable ratings and the match coefficients will attain the maximum value of +1 if all buildable features are present, and the sum of products of the non-buildable rating and the match coefficient will attain the minimum value of −1 if all non-buildable features appear in the designs. The net algebraic total of the above two sums is multiplied by 21 [which is equal to $100_{\text{(maximum attainable score)}} - 69_{\text{(maximum construction system score)}} - 10_{\text{(maximum bonus)}}$] to reflect the buildable and the non-buildable features of a schematic design. The buildability score of a schematic design is the sum of the buildability score from construction system, innovation bonus, and buildable and non-buildable features.

2.3 Buildability Study in Southeast Asia

In Indonesia and Malaysia, the studies of constructability have been done on the implementations and the practices of construction industry practitioners. By adopting the constructability concepts of CII, an assessment was conducted on the understanding and the application of the constructability among Malaysian engineers (Nima et al., 2001b). A further study was conducted to assess the familiarity of the Malaysian building contractors with the constructability concepts and activities (Saghatforoush et al., 2009). The implementation as well as the problems and the barriers of constructability during different stages of construction were evaluated through case studies in Indonesia (Trigunarsyah, 2004c). Moreover, the practice and the impact of constructability on project performance were also investigated among the Indonesian construction contractors (Trigunarsyah, 2004a). Meanwhile, the study in Thailand concentrated more specifically on proposing guidelines for buildable design of a factory and the framework for its evaluation (Pattaranawic and Tongthong, 2003). A model was created to assess the buildability of the design at design stage based on the concepts of Code of Practice on Buildability in Singapore.

2.4 Factors Related to Buildability

In the BDAS of BAC, the main factor that attributes to higher buildability is less manpower consumption. The building system that requires less workers is considered as more buildable. This main factor is extended to the principles of standardization, simplicity and single integrated elements (BCA, 2013).

In the BAM, the buildability of building designs are based on 9 factors which are: allowing economic use of contractor's resources, enabling design requirements to be easily visualized and coordinated by site staff, enabling contractors to develop and adopt alternative construction details, enabling contractors to overcome restrictive site conditions, enabling standardization and repetition, enabling freedom of choice between prefabricated and onsite works, enabling simplification of construction details in case of non-repetitive elements, minimizing the impacts due to adverse weather by enabling a more flexible construction programme, and allowing design to achieve safe construction sequences on site (Wong, 2007).

The buildability factors of in-situ reinforced concrete building components were studied by Jarkas. He quantified the relationships between buildability factors and the actual productivity. For reinforced concrete columns, the buildability factors that impact the productivity of formwork installation are grid patterns, variability of columns sizes, repetition, total and average shutter size, and geometry (Jarkas, 2010c). The buildability factors that affect the rebar fixing productivity of reinforced concrete beam are variability of beam sizes, rebar diameter, stirrups diameter, reinforcement quantity, beam dimensions, and span geometry (Jarkas, 2010d). The main and the interactive effects of rebar diameter, reinforcement quantity, slab geometry, and reinforcement layer location on rebar fixing productivity of beamless slabs are determined (Jarkas, 2010b). The buildability factors that influence micro-level formwork labor productivity of slab panels are repetition, panel areas, and geometry of panels (Jarkas, 2010a). The buildability factors of in-situ reinforced concrete walls on rebar installation labor productivity are quantity of reinforcement installed, wall thickness, plan geometry, and wall curvature intensity (Jarkas, 2012). These buildability factors could be consolidated as variability of size of building components, rebar diameter, reinforcement quantity, geometry, dimension, and grid pattern. These factors are the attributes of standardization and simplicity.

Safety is an important aspect of buildability. The early design outcomes that influence the safety could be categorized into five broad issues: access, material handling, fall protection, material substitution, and construction process (Weinstein et al., 2005). Early consideration of buildability and safety by the designers, and the experienced contractors if possible, is an important step to improve construction worker safety (Hecker and Gambatese, 2010).

2.5 Boundaries of Buildability and Constructability

By reviewing the literature about the development of buildability and constructability concepts, it is clear that the constructability has wider boundaries than the buildability. Buildability is the concept that focuses mainly on the extent to which the design facilitates the construction as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building works (BCA, 2013). On the other hand, constructability considers various phases of building construction, including the design, the procurement, the site operation, and even the operation and the maintenance ((CII), 1987, Ardery, 1991, Pepper, 1994, Russell et al., 1994b, Anderson et al., 2000, Arditi et al., 2002, Saghatforoush et al., 2011, Saghatforoush et al., 2012). The successful implementation of the constructability depends upon the involvement of the project owners (Gugel and Russell, 1994, Russell et al., 1994a, Trigunarsyah, 2004a), the designers (Glavinich, 1995, Staub-French, 2003, Lam et al., 2005, Trigunarsyah, 2007), and the contractors (O'Connor and Davis, 1988, Nima et al., 2001a, Song et al., 2009). Early involvement of the construction experts during the design development stage is essential since the ability to obtain the tangible benefits of the project life cycle is greater in the initial stage of project development (Ardery, 1991, Griffith and Sidwell, 1997, Francis et al., 1999, Trigunarsyah, 2004b, Song et al., 2009).

2.6 Benefits of Constructability Improvement

Nowadays, the construction clients expect more than to complete the project on time, within budget, and with good quality. They require an accident free project with the final product to be inexpensive to operate and maintain. The efficiency and the effectiveness of the project are viewed from the life cycle perspective, and this is where the constructability concepts and principles could contribute.

The Business Roundtable reported a potential return on investment of 10:1 when constructability was applied (1982), while the case studies on construction projects in Indonesia indicated a benefit-cost ratio of about 45:1 for improvement in constructability (Trigunarsyah, 2004a). Subsequent studies have confirmed that integrating the construction knowledge into the design processes reduces the total costs of a project (Ireland, 1985, Ardery, 1991, Russell et al., 1992, Griffith and Sidwell, 1997, Jergeas and Put, 2001, Trigunarsyah, 2004c). The construction bid could be estimated more accurately (Gibson et al., 1996). Increased constructability also has a positive relationship with increased site productivity as fewer labors are needed (Poh and Chen, 1998, Lam, 2002), and the duration of the construction is reduced (Griffith and Sidwell, 1997, Eldin, 1999, Francis et al., 1999, Trigunarsyah, 2004a, Trigunarsyah, 2004c).

Constructability is also associated with intangible benefits in terms of higher quality for the completed work (Eldin, 1999, Francis et al., 1999, Trigunarsyah, 2004b), and improved safety during construction (Francis et al., 1999, Trigunarsyah, 2004b, Trigunarsyah, 2004c). Additional identified payoffs include the reduction in the number of construction problems and claims (Eldin, 1999, Trigunarsyah, 2004a), the improvement in communication and teamwork (Francis et al., 1999), and enhancement of the satisfaction of project personnel and clients by meeting all project objectives (Russell et al., 1992, Eldin, 1999, Francis et al., 1999).

2.7 Approaches to Improve Buildability

By reviewing the literature, four common approaches to improve the buildability were found. The first two approaches which focus on improving the design process are buildability guidelines and computerized systems, while the other two approaches which focus on improving the design result are buildability review and quantitative assessment.

Buildability principles and guidelines are the approach to improve buildability by providing the designers with general recommendations to implement the buildability in a project. A series of publications were issued to offer a comprehensive guidance and specific insight into how the buildability could be implemented. These publications include Highway Constructability Guide which offers an overview of constructability enhancement program (Hugo et al., 1990), Constructability Implementation Guide which offers a complete set of 17 tools that address both corporate- and project-level constructability programs ((CII), 1993), Constructability Manual which advises construction project teams on how to improve constructability (Francis et al., 1996), Constructability Guidelines which offers a constructability implementation policy at every phase of a project ((CII), 1997), and Guideline for Design for Constructability which focuses on constructability of steel bridge (AASHTO/NSBA, 2003). The objective of these guidelines is to stimulate the concepts of buildability during the design phase rather than to provide a complete checklist which limit the creativity of the designers.

Computerized systems offer a detailed assessment of each building component over various aspects of constructability. The knowledge based computer models extract the knowledge from experienced designers and contractors to assess buildability of a design qualitatively. Expert system was used to formalize constructability knowledge related to design decisions, to integrate design and construction during the early project phase (Fischer and Tatum, 1997). A knowledge model was developed to automate constructability assessment of steel frame structures (Ugwu et al., 2004). Artificial neural network (ANN) technique was also used for the assessment of beam-design constructability (Zin et al., 2004). On the other hand, quantitative buildability assessment by an application could provide design effects and recommendations for correction to the designers simultaneously. A fuzzy Quality Function Deployment (QFD) for quantitative buildability evaluation at the early design phase was developed based on the mechanisms of conventional QFD methodology and fuzzy set theory (Yang et al., 2003). Based on the planned construction process, a construction planning application and a weighting system were developed using artificial intelligence to evaluate the buildability factors of a design (Hassan and Abdul Karim, 2008). The object-oriented Building Information Modeling (BIM) and the 4D CAD simulation model were integrated to evaluate the constructability of different designs in a more accurate and faster way (Hijazi et al., 2009).

Constructability review is another approach to evaluate the buildability of designs. Formalized intermediate-sized constructability review program was found to be effective in reducing project durations without increasing cost (Ford et al., 2004). Many design firms have a formal (explicit) constructability program that is launched as early as the conceptual planning stage of the project (Arditi et al., 2002). In-house design-phase constructability review by design-review team totally independent of the design team was suggested to improve the constructability (Glavinich, 1995). Constructability reviews were integrated into the project development of transportation projects to ensure rational bids and minimize problems during construction (Anderson et al., 1999). Analytical tools were integrated into constructability review process (Fischer and Tatum, 1997). 3D/4D models were used to support the knowledge communication and generation during the constructability review process (Hartmann and Fischer, 2007).

Quantitative assessment models offer the designers a simple procedure to evaluate the buildability based on some buildability factors and the weightings of building components. This approach was adopted by the Buildable Design Appraisal System (BDAS) and Constructability Appraisal System (CAS) in Singapore (BCA, 2013). Similar models were developed in Hong Kong (Wong, 2007) and in Malaysia (Nourbakhsh et al., 2012) to suit the buildability factors of these countries. A scheme design buildability assessment model was developed to evaluate the buildability of designs at early design stage (Lam et al., 2012). This approach requires minimum effort to assess the buildability of each building elements and the design as a whole (Wong, 2007). The results of assessment from the above mentioned models can also be used to benchmark different designs.

2.8 Building Construction Industry in Cambodia

The building construction industry in Cambodia is less developed than in its neighboring countries, such as Thailand and Vietnam (Subramaniy, 2013). Most of the existing and newly constructed buildings are low-rise reinforced concrete (RC) buildings. However, the number of mid- and high-rise buildings has recently increased in the capital city, Phnom Penh, and the tourist cities, such as Siem Reap and Sihanoukville.

In-situ RC structure is the most popular type of structure used in Cambodia for low-, mid- and high-rise buildings. A pre-stressed slab system is used only in a few mid- and high-rise buildings, especially in designs of commercial building. The installation of post-tension cables and post-tensioning works are normally subcontracted to a specialized subcontractor. The main contractor is responsible for installing the formwork and reinforced steel, and pouring the concrete. These main contractors have begun to realize the benefits of lower overall costs and shorter construction times of flat post-tensioned slabs.

Steel structure is typically used in factory construction to satisfy the requirements for a shorter construction time and for the mobility of the client. Steel trusses are widely used for factory construction, but pre-engineered steel frames have been entering the market. Precast components are mostly used for short to medium span bridge constructions and pilings. There are no fully precast building constructions in Cambodia, and owners also have little understanding and confidence in them. Composite columns are used only in skyscraper projects, but composite floors are not yet being used.

Design-Bid-Build (DBB) is the dominant procurement practice in Cambodia, because the project owners are most familiar with it and want to compare the bid prices among contractors. The project owners concentrate their attention on minimizing the expense of preliminary study, design and construction. The owners do not show much interest in the costs of operation and maintenance, and do not have much trust in the contractors. Due to the DBB procurement method, contractors do not have much input for design buildability. Instead of providing suggestions about the designs in their bidding documents, the contractors simply adjust the bid price if the designs are difficult to construct. Low labor costs discourage the contractors from using advanced construction techniques and equipment to automate the construction process.

The requirements of the owner are the top priority of the designer and the contractor. The requirements of the owner are translated into drawings and specifications. It is the contractor's responsibility to complete the project accordingly, the contractor could only give buildability feedback to the designer during the construction phase. Even if the feedback has been given, the designers modify the design only to the extent that it does not complicate the design process. Some experienced designers incorporate standardization and simplicity in design, except for prefabricated components.

Most of the low skilled workers in Cambodia are migrant workers who are farmers during the harvesting season, but at other times work as construction workers. Therefore the supply of construction workers is not stable. In contrast, the majority of skilled workers and superintendents are permanent workers and available year-round. There is a noticeable number of skilled Vietnamese workers in Cambodia. Due to higher working wages, more and more laborers are attracted to work in foreign countries, such as Thailand, Malaysia and South Korea.

2.9 Conclusion

Buildability rules and guidelines provide the designers the considerations of all buildability problems from past experience at various project stages. However, the implementations of the buildability rules and guidelines are subjective and the assessment process can be complicated. The guidelines are difficult to cover every design process, and the results of application are abstract. The computerized system gives the designers an automated assessment of the buildability during the design process. It provides specific recommendations and easy corrections of design details. On the other hand, the computerized system requires computer expertise to build and update the knowledge. Moreover, the current computerized systems are applicable only to a specific building system, and have difficulty to integrate with different design software. Buildability review is a popular approach to improve buildability which tries to eliminate the problems in design drawings and specifications before the construction. It is easy to conduct and becomes more powerful when use in conjunction with 3D/4D models. Nevertheless, the review processes depend heavily on personal experience, and incur additional time and resources. The designers might also be reluctant to accept the suggestions of the reviewers. Quantitative assessment models enable an objective evaluation of the designs based on buildability attributes and the results obtained are comparable. These models are easy to understand, require minimal resources to apply in real practice, and can be applied for different building systems. The assessment results of the models can also be updated easily. Nonetheless, these models consider only a limited number of buildability factors that depend on the specific characteristics of each construction industry.

Based on the literature about buildability and constructability, quantitative assessment models are found among the four approaches to be the most viable and achievable way to improve buildability in Cambodia. This approach has been successfully implemented in Singapore through BDSA since 2001 with various concrete positive effects. However, the BDSA focused only on the productivity of labors of various building types without considering the requirements of equipment, skills, technologies, and materials costs. On the other hand, in addition to labor productivity, the BAM also considered the restrictive site conditions for the evaluation of buildability.

In contrast, the Cambodian construction industry is less developed, has lower labor costs, less advanced construction equipment and techniques, less sloped and less congested site conditions, and the construction practitioners are less familiar with the buildability concepts. Therefore, a model to comprehensively evaluate the buildability of building designs based on localized buildability factors at early phase of design is needed.

CHAPTER III
RESEARCH METHODOLOGY

This chapter discusses about the research methods to identify the important factors that influence the buildability, to construct a model to evaluate the buildability of building designs, and to validate the model. In this research, triangulation – the use of qualitative and quantitative techniques together with theories and literature from previous studies – was used to study the topic. First, the research approaches were explained, followed by the research design and research framework. Then the processes of data collection and analysis for each phase of the surveys were described.

3.1 Research Approach

Research could be broadly categorized into two distinct types: qualitative and quantitative. Qualitative approaches search for insight and people's perception of the world through people's opinions, beliefs, understandings, and views, while quantitative approaches attempt to collect factual data and to study the relationships between facts (Fellows and Liu, 2008).

Qualitative method attempts to take account of differences between people where propositions may develop not only from practice, or literature review, but also from the ideas themselves. It is an approach to study the social world, to describe and analyze the behavior of humans and their groups from the point of view of those being studied (Amaratunga et al., 2002). Qualitative data are useful to supplement, validate, explain, illuminate, or reinterpret quantitative data gathered from the same setting.

Quantitative method concerns the truth-value of propositions, measures the variables, and is used to verify reliability through comparative analysis, statistical analyses, and repeatability of data collection (Amaratunga et al., 2002). It helps to search for causal explanations and fundamental laws, and generally reduces the whole to the simplest possible elements in order to facilitate analysis (Easterby-Smith, 1991).

Both quantitative and qualitative methods have inherent weaknesses (Easterby-Smith, 1991). Quantitative methods tend to be rather inflexible and artificial, not very effective in understanding processes or the significance that people attach to the actions, and fail to ascertain the deeper underlying meanings and explanations. The data collection of qualitative methods is tedious, the analysis and the interpretation of data may be more difficult.

In triangulated studies, two or more research techniques, qualitative and quantitative approaches, are employed to compensate the weakness of each single method by the counter-balancing strengths of an individual method with another (Amaratunga et al., 2002). Quantitative data can complement the qualitative study by finding a representative sample, locating deviant samples and enable statistical testing of the strengths of relationships, while qualitative data can help the quantitative study by conceptual development, and understanding the underlying explanations of significance.

In this research, the qualitative approaches are used to identify the factors that affect the buildability, the subcriteria to evaluate these factors, the current practices of designs, and to validate the buildability evaluation model. The quantitative approaches are employed to determine the level of importance and the weight of the buildability factors, and to develop the buildability assessment model.

3.2 Research Design

Research design is necessary because it guides the various research operations and makes the research more efficient to yield maximal information by spending minimal effort, time and money (Kothari, 2004). This section lays the plan for data collection and analysis, which consists of several steps. The first step is to identify the factors that affect the buildability and the existing model for buildability evaluation from the literature. The second step is to conduct a pilot survey to verify these factors, to collect additional factors, and to study the level of importance of these factors. The third step is to develop a questionnaire and to perform large-scale surveys to determine the level of importance of these buildability factors. Interviews are conducted in parallel with the questionnaire survey to understand the reasoning of the interviewees. The fourth step is to analyze the data using mean and one-sample *t*-test. Then a buildability evaluation model is developed based on the analytical hierarchy process. Finally, this model is validated by scoring of actual projects and in-depth interviews with local construction practitioners.

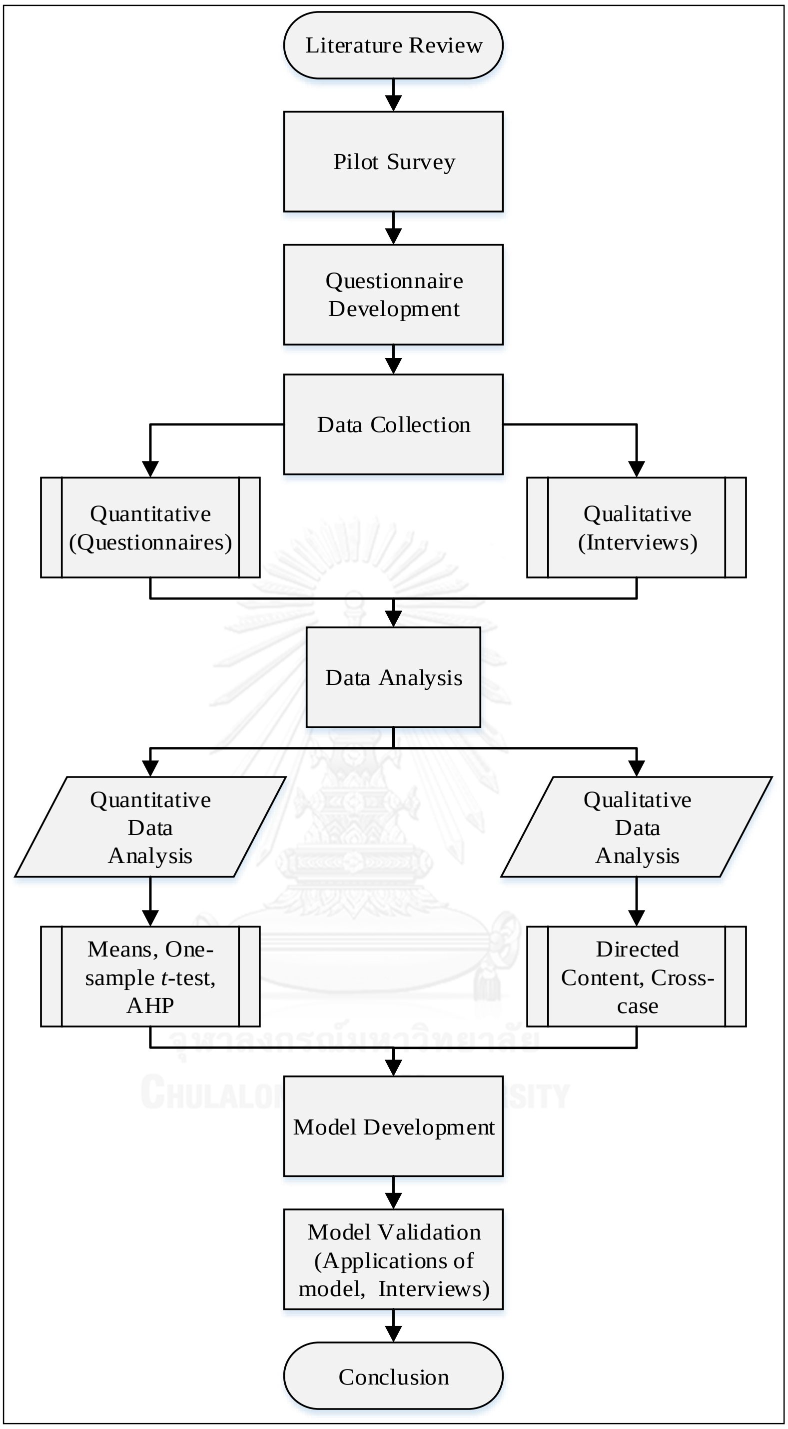

Figure 3.7 Research Framework

3.3 Methods of Data Collection

There are two types of data, primary and secondary. The primary data are those which are collected for the first time without any process. The secondary data are those which have been collected by someone else and have been analyzed. In this research, the buildability factors and the current assessment models are secondary data collected through literature reviews. On the other hand, the data of interviews and surveys in this research are primary data.

3.3.1 Quantitative Data Collection

The quantitative data in this research were collected through the survey questionnaires. Pilot survey was conducted before the main survey with experts to improve the completeness of the factors and the comprehensibility of the wordings. Unstructured questionnaires were used in the pilot survey because it is effective in primary exploration of the topic and acquisition of a wide range of data (Kothari, 2004). The goals of pilot survey was to get the general perceptions of the construction experts about the buildability, the factors that affect buildability, and the approaches to improve buildability, and to complement and validate the knowledge from the literature. The respondents of the pilot survey are the project managers and site engineers of building projects in Phnom Penh. The respondents were interviewed for their opinions, understandings and comments regarding the questions in the pilot survey.

Based on the results of the pilot survey and literature reviews, the main questionnaire was designed for large-scale data collection. The questionnaires were delivered and explained to each target respondent personally to avoid misunderstanding and to increase the rate of response. The large scale data collection of main questionnaire was divided into two parts, the first part was the evaluation of level of importance of buildability factors by using 5-point Likert Scale, and the second part was the structured questionnaire using the analytical hierarchy process (AHP) in which the respondents were required do pairwise comparisons of the buildability factors.

Judgmental and convenience sampling of the deliberate sampling techniques were used for quantitative data collection in this research. Judgment sampling was used in the pilot survey because it was important that the respondents possess adequate experience and insight of the construction industry. In judgment sampling, the samples are selected subjectively for their representativeness of the population (Kothari, 2004). Convenience sampling was used and considered desirable for large-scale survey in this research because it was difficult to get a complete list of target population, to contact and get response from the target respondents. Moreover convenience sampling has advantages over other sampling methods in costs and time required. In convenience sampling, population elements are selected for inclusion in the sample based on the ease of access (Kothari, 2004).

3.3.2 Qualitative Data Collection

Qualitative data were collected through direct personal interviews in two phases. The first phase was to understand the reasoning of the importance level of the factors and the second phase was to understand the reason of the weights and the scoring assigned of the model.

The initial structured interview was conducted concurrently with main questionnaire to save time and costs of the data collection, and to ensure that the respondents still have fresh memories of their selections. The last in-depth interviews were carried out to gather the opinions of experts on the weights and the scoring of the model. Friendly atmosphere of trust and confidence was created so that the respondents feel at ease while talking and discussing. Before the commencement of questioning and interview, the purpose and the keywords used were explained clearly to the respondents. The interviews should start from easy, expected and impersonal questions toward more difficult and intimate. All effort should be made to keep the respondents on track and discouraging the irrelevant conversation.

The convenience sampling was used in the main questionnaire for the same reasons mentioned in the initial structured interview. The purpose of using deliberate sampling in last interview was to apply the model in the typical construction projects in which the opinions of the experts are applicable for the designs of common building construction projects.

3.4 Sample Size

The sample size needed to identify the level of importance of the buildability factors is at least 30 respondents (see 3.5.4 for more details).

The target sample size used to develop the buildability assessment model is between 12 and 15. The target number of projects to study the current practices of design is at least 5.

3.5 Data Analysis

Qualitative and quantitative data were analyzed using different approaches. There were three main purposes to analyze the data. First, the data were analyzed to find out the level of importance of the buildability factors. Second, the additional data were further collected and processed to develop the model for buildability evaluation. Third, the data of model scorings and the impressions of the experts were discussed for conclusion.

3.5.1 Qualitative Data Analysis

There are three distinct approaches of qualitative content analysis: conventional, directed, and summative (Hsieh and Shannon, 2005). Directed content is used in this research.

During the pilot survey, the opinions of the respondents on the factors that affect the buildability are collected by highlighting the transcripts. A predetermined codes of factors are prepared before the interview based on the literature. In direct content analysis, data are categorized immediately with the predetermined codes. Data that cannot be coded are identified and analyzed later to determine if they represent a new category or a subcategory of an existing code. The categories should be exclusive and exhaustive (Fellows and Liu, 2008). It is important to be open-minded and unbiased during the categorization. Qualitative content analysis of the pilot survey is to find a complete list of factors and to sort them in groups.

The analysis of the structured interviews during the main survey and the validation survey were to determine the reasons of the level of importance, the weight of the buildability criteria and factors. In structured interview, the same questions are asked in the same sequence and manner to different interviewees (Phellas et al., 2011). The interviews were conducted face-to-face to increase the rate of response, to explain questions to the interviewee, to avoid incomplete answers, and to discuss more extensively through interaction, and to get more details. Opinions and suggestions of the respondents regarding the model were also incorporated into the final model development. The interviews were transcribed and subjected to iterative analysis. There are three processes in the analysis: data reduction, data display and conclusion (Folkestad, 2008). The data reduction starts at the very beginning of research phase when concepts are formed and subjects are selected. Then the meanings of some part of the data are explored in data display phase and the final findings are compared, contrasted, searched for patterns and triangulated for conclusion.

Cross-case analysis was used to find the subcriteria and the current practices of design to evaluate the buildability factors. Cross-case analysis is a method of grouping together common responses of the interviews as well as analyzing different perspectives of central issues (Patton, 1990). The opinions of the respondents on the subcriteria of each buildability from different cases were summarized and grouped together.

3.5.2 Internal Consistency Analysis

The two concerns when one instrument is used to perform a test are validity and reliability. Validity is the extent to which one instrument is measuring what it is intended to measure, while reliability is the extent to which that instrument could be measured consistently (Tavakol et al., 2008). The reliability of an instrument is the prerequisite for, but does not depend on, its validity (Nunnally and Bernstein, 1994). Before a test can be used for examination or research purpose, its internal consistency should be determined. Cronbach's coefficient alpha was developed by Lee J. Cronbach in 1951 to estimate the internal consistency of a test or scale (Cronbach, 1951). It is one of the most important and widely used statistics in research involving test construction and use. The calculation of Cronbach's alpha should be performed for each concept rather than for the entire test. The value of Cronbach's alpha varies between 0 and 1 where the higher value implies higher consistency. The alpha is also affected by the number of questions, the number of dimensions, the interrelatedness between items, and the multidimensionality (Cortina, 1993). Provided sufficient number of items, the value of alpha can be high in spite of the low average items intercorrelations or multidimensionality. A too high alpha may suggest that some items in the questions are redundant and should be removed (Tavakol and Dennick, 2011).

3.5.3 Concordance Analysis

Kendall coefficient of concordance (W) was used to test whether the buildability factors can be prioritized. The null hypothesis (H_0) is that the sample sets of ranking are independent or unrelated at 95% confidence interval. This coefficient was used by

Aibinu and Odeyinka (2006) to rank the construction delay factors of the projects in Nigeria, and by Nkado (1995) to rank the construction time-influencing factors of the buildings in the U.K. When the number of variables, in this case the buildability factors, is at least 8, an approximate test could be run based on chi-square distribution with ($N-1$) degree of freedom (Siegel and Castellan, 1988). The test is given by

$$chi\ square\ (\chi^2) = m(N-1)W$$

where m = number of respondents; N = number of factors being considered, W = Kendall coefficient of concordance.

A sample size of 20 and over is considered as adequate in order to apply the chi-square test (Naoum, 2007).

3.5.4 One-Sample *t*-test

One-sample *t*-test was used to determine the level of importance of each buildability factor. The test is run by comparing the score of every sample of one factor with the predetermined cutoff point. In this research, one-tailed *t*-test was conducted to check if the mean score of each factor is significantly greater than 3.5 at 95% confidence level. A factor is considered important if its p value is less than 0.05. A minimum sample size of 30 is considered large enough for the two-sided t interval to have proper coverage (Boos and Hughes-Oliver, 2000).

One-sample *t*-test with five-point Likert scale was used by Aibinu and Odeyinka (2006) to determine the importance of the factors contribute to the construction delay in Nigeria. The cutoff point of 2.5 was selected in their study, but they did not provide the reason of why this value is selected. Similarly, in the study of Hwang et al. (2014) in investigating the causes of client-related rework in building projects, one-sample *t*-test with five-point Likert scale was used to determine the frequency of the causes. The mean score of 3.00 was selected as the cutoff point without providing any arguments of the value selected. Therefore, it could be concluded that the cutoff values in these studies were arbitrary values greater than or equal to the means of each and all the factors considered. The cutoff value also depends on the distribution of the samples. The cutoff value is higher if the value of the distribution of the sample is high.

In this study, the cutoff point of 3.5 was selected to test the level of importance of the buildability factors. It is a value slightly greater than the previous study since the distribution of the sample of this study is also higher than the distribution of those in the previous studies. The value of 3.5 is also the minimum value of the means of all the factors studied.

3.5.5 Analytical Hierarchy Process (AHP)

Analytical Hierarchy Process (AHP) is a multiple criteria decision-making tool that has been used in various applications related to decision-making (Vaidya and Kumar, 2004). This theory was developed by Professor Thomas L. Saaty in 1971 in the U.S. (Saaty, 1980). The AHP is a theory of measurement through pairwise comparisons and relies on the judgment of expert to derive priority scale (Saaty, 2008). In the AHP, the factors that are important for a particular decision are selected and arranged in a hierarchic structure descending from an overall goal to criteria, subcriteria and alternatives in successive levels (Saaty, 1990). Pairwise comparisons of every element in the lower level are conducted based on a single element of the next higher level to obtain a priority vector. This process continues until the highest level. By consolidating the priority vectors of each lower level, the priority vector of the next higher level is calculated. However, a hierarchy in the AHP does not need to be complete, an element in a given level does not have to function as a criterion for all the elements in the level below (Saaty, 1990).

The basic problem with a hierarchy is to seek the understanding at the highest levels from the interactions of various levels of the hierarchy rather than directly from the elements of the level (Saaty, 1980). The most valuable part of the AHP is to make consistent judgment by comparing only two things based on a single criterion, this is exactly the basic concept of the AHP. The four axioms of the AHP are (Saaty, 1986):

(1) The reciprocal property in making paired comparisons
(2) Homogeneity in making paired comparison among similar thing with respect to a common criterion and thus to prioritize all elements in the same level based on that common criterion
(3) The higher level depends on the next lower level
(4) Expectations are well represented in the hierarchy.

There are four steps in the AHP to solve a decision problem, namely set-up of the decision hierarchy, data collection by pairwise comparisons, determination of relative weight of decision elements, and aggregation of the relative weights of decision elements (Zahedi, 1986).

The first step is to break down the decision problem into a hierarchical structure. The AHP model used in this study consists of five hierarchical levels. The goal of our problem is to select the most buildable design, which is placed on the first level.

The second level of the hierarchy is the criteria to evaluate the designs. These criteria are design documents, resources, flexibility to changes, construction safety (safety-in-design), and site layout.

The third level of the hierarchy is the subcriteria defining the five criteria in the second level. There are seven subcriteria for design documents, four subcriteria for resources, and four subcriteria for flexibility to changes, and five criteria for construction safety and site layout. The criteria and the subcriteria in this model could be evaluated by pairwise comparisons using the basic AHP approach in which the comparisons are made between the elements in the lower level with respect to every parent element in the upper level.

The fourth level of the hierarchy consists of the rating scale used to evaluate each subcriteria given a specific alternative. This level of hierarchy is different from the usual AHP in that instead of performing direct pairwise comparisons among the alternatives for each subcriterion, a five-point rating scale is used to evaluate each alternative under each subcriterion. The use of rating scale instead of pairwise comparison was pioneered by Liberatore (Liberatore, 1987, Liberatore et al., 1992), and was applied to decision making in business (Tam and Rao Tummala, 2001) and medical and health care decision making (Liberatore and Nydick, 2008). The advantage of using this method is to overcome the number of pairwise comparisons when the number of criteria, subcriteria, or alternatives are large.

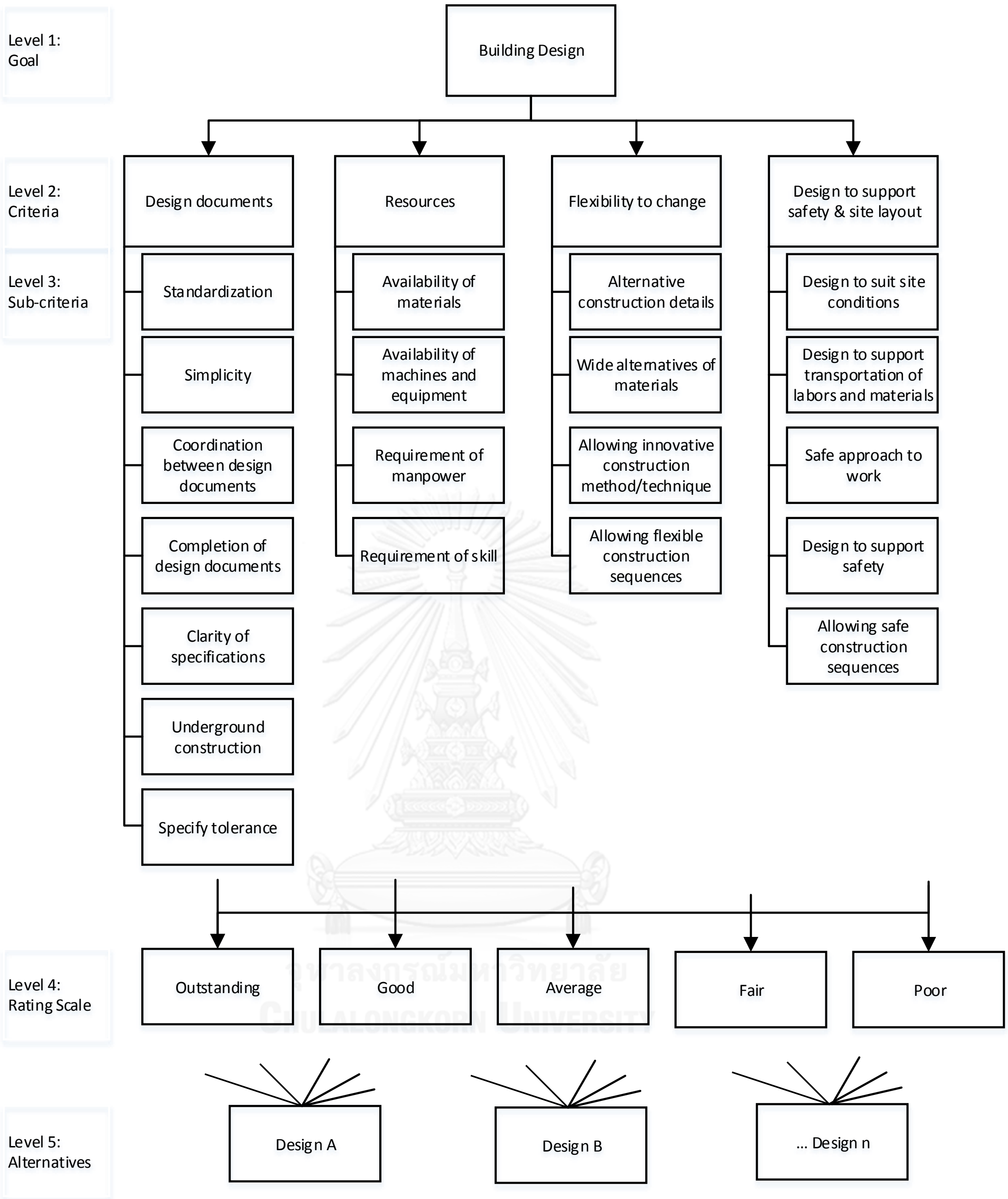

Figure 3.8 AHP Hierarchy Structure

	O	G	A	F	P
O	1	3	5	7	9
G	1/3	1	3	5	7
A	1/5	1/3	1	3	5
F	1/7	1/5	1/3	1	3
P	1/9	1/7	1/5	1/3	1

Table 3.1 Pairwise Comparison Judgment Matrix for Five-Point Rating Scale

In the studies of Liberatore, he used five-point rating scale of outstanding (O), good (G), average (A), fair (F) and poor (P) (Liberatore et al., 1992, Liberatore and Nydick, 1997). The difference between two adjacent scales is constantly two times as shown in the pairwise comparison judgment matrix in Table 3.1. The eigenvector of this matrix of outstanding, good, average, fair and poor are 0.513, 0.261, 0.129, 0.063 and 0.034, respectively.

The lowest level of the hierarchy consists of the alternatives, namely the building designs to be evaluated. Unlike the usual AHP which requires at least two alternatives, this model is also applicable for only single alternative. A baseline score can be established to be the threshold for the acceptance if the consensus among the users can be reached.

The second step is to assign the value of pairwise comparison to the criteria and the subcriteria in the second and the third level in the hierarchy. The nine-point scale (see Table 3.2) suggested by Saaty is used for the pairwise comparisons between the elements (Saaty, 1980). The data are collected in the form of matrix in which the elements in rows and columns are the same. The value of the diagonal elements of the matrix is equal to one, and the lower triangle elements are the reciprocal of the upper triangle elements. Therefore, the respondents are required to make the pairwise comparisons only for the upper triangle elements.

The third step is to determine the relative weight of the subcriteria and the criteria of each individual respondent and then combine them together. The eigenvalue of the criteria and the subcriteria are calculated for each respondent, and their consistency is also checked. The consistency of the matrix in paired comparisons can be measured by a number λ_{max} (called the maximum or principal eigenvalue). The closer λ_{max} is to n (the number of activities in the matrix) the more consistent is the result

(Saaty, 1980). The deviation from consistency may be represented by ($\lambda_{max} - n$) / (n – 1) called consistency index (CI). This value is then compared with the same index obtained as an average over a large number of reciprocal matrices of the same order whose entries are random. The ratio of CI to that random matrices is called the consistency ratio. A CR of 0.1 or less is considered acceptable.

Intensity of importance on an absolute scale	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values between the two adjacent judgments	When compromise is needed
Reciprocals	If activity *i* has one of the above numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compare with *i*	
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Table 3.2 The Fundamental Scale of AHP

As the objective of this research is to develop a buildability assessment model of building designs for the constructions in Cambodia, the standard AHP is adapted in order to aggregate the group decisions. Ishizaka and Labib (2011) suggested that there were four ways to combine the preferences of the individuals to reach a consensus. The four mathematical methods are summarized in Table 3.3. The geometric mean is the only way to combine the judgments to assure reciprocal property in which the final outcomes of the hierarchy of each expert are aggregated instead of just combining their judgments (Saaty, 2008). Therefore, the geometric mean on judgments is adopted in this study to aggregate the judgments of the experts to get the weight of buildability factors instead of the priorities of the alternatives. The priorities of alternatives are evaluated by the rating scale. A program named Expert Choice is used to facilitate the calculation.

		Mathematical aggregation	
		Yes	No
Aggregation on:	Judgments	Geometric mean on judgments	Consensus vote on judgments
	Priority	Weighted arithmetic mean on priorities	Consensus vote on priorities

Table 3.3 Four Ways to Combine Preferences (Ishizaka and Labib, 2011)

The fourth step is to synthesis the relative weights from the third step with respect to all lower levels of the hierarchy in order to get the global vector of composite weights. The global composite weight of each subcriterion (the buildability factors) is then multiplied by the five-point rating scale of Liberatore and summed together to get the final rating of a decision alternative to achieve the general objective of the problem.

3.6 Conclusion

This chapter describes about the process in conducting the research. Triangulation – literature, qualitative, and quantitative – method was used in this research. The literature was reviewed for the concepts, the practices, and the factors that affect the buildability to draft the questionnaire for pilot survey. The validity and the clarity of the questionnaire items were tested in the pilot survey through the collection of the experts' opinions. Based on these, the main questionnaire was modified and improved before conducting the large-scale data collection. The pairwise comparisons of the AHP and the interviews were conducted in the main questionnaire. The AHP was used to collect the quantitative data while the interviews were used to get the arguments of the scorings. The quantitative data were analyzed and transformed into a buildability evaluation model. This model was validated by scoring of actual building designs and in-depth interviews with the construction experts.

CHAPTER IV
IDENTIFICATION OF IMPORTANT BUILDABILITY FACTORS

In this chapter, the process of quantifying the perception of the contractors on importance level of buildability factors was described. First, the characteristics of respondents of the survey were illustrated, together with their experience and positions. Then each buildability factor was introduced, the process of analysis and the result of the data analysis were discussed. Next, the current practice of each buildability factor in Cambodia was described to provide further details of the quantitative data. The results of this chapter were used as the input to determine the weight of buildability factors and to develop the buildability assessment model.

4.1 Description of Data Collection

The main questionnaire of this study was divided into three parts. In the first part, the respondents were asked to evaluate the buildability by using 5-point Likert scale. This chapter corresponds to the main questionnaire survey. In the second part, the respondents were required to make pairwise comparisons of the buildability factors. The questionnaire was ended by the interview about the criteria to evaluate the buildability factors and the level of satisfaction of the current practice related to these buildability factors. The respondents were free to select and conduct one or more parts of the questionnaire according to their availability. The respondents are site engineers, project managers, and directors of the contractors of mid- and high-rise building construction projects in Phnom Penh city. The city was selected because it is the capital city of Cambodia, the center of politics and commerce where the headquarters of most construction companies are located. The questionnaires were distributed through personal contacts.

The data were collected in two phases. The first phase was conducted from January 4 to 14, 2014 with 10 experienced engineers as the pilot survey to test if the factors are complete and clear, and the wordings in the questionnaire is appropriate. The second phase took place from March 16 to April 6, 2014 for the full scale survey.

Thirty-five valid answers for the first part and eighteen valid answers for the second and third part of the questionnaire were collected for analysis. The length of time that the respondents spent for the questionnaire varied from thirty minutes to two hours depending on the parts that they selected.

Experience at construction site is one of the main selection criteria of the respondents. All of the respondents have at least two years' experience working with mid- and high-rise building projects, and hold at least bachelor's degree in civil engineering. More than half of the respondents have experience between 5 and 10 years and the average year of experience of all respondents is at 8.94 years. Table 4.1 summarizes the experience of the respondents. The results of evaluation of all the respondents on importance level of each buildability are attached in Appendix A.

Table 4.4 Experience of Respondents

Experience on site	Number of respondents	Percentage	Cumulative Percentage
Less than 5 years	9	26%	26%
5 to 10 years	18	51%	77%
10 to 15 years	4	11%	89%
More than 15 years	4	11%	100%
Total	35	100%	

Table 4.5 Positions of Respondents

Position	Number of respondents	Percentage	Cumulative Percentage
Director	4	11%	11%
Project Manager	16	46%	57%
Construction Manager	4	11%	69%
Site Engineer	11	31%	100%
Total	35	100%	

4.2 Factors related to Buildability

The buildability factors from literatures are reviewed and the factors related to design output are summarized and grouped into (1) Design Documents; (2) Design for Available Resources; (3) Flexibility to Changes; and (4) Design to Support Site Layout and Construction Safety. To ensure that the wordings of the factors are comprehensible and that some other important factors are not overlooked, a pilot survey with 10 experienced engineers were conducted. In total, 20 factors were identified. Table 4.3 shows the 20 factors under the four categories.

The 20 factors were used to develop the questionnaire to sample the opinions of project managers and engineers of contractors in building construction. The purpose of the research, the definition of buildability and the description of each buildability factor were written on the questionnaire to improve the comprehensibility and assure common ground of understanding for each respondent. The importance level of each buildability factor was evaluated by 5-point Likert Scale where a value of 5 denotes very high importance and a value of 1 indicates very low importance. The respondents were asked to assign the importance of each factor from 1 to 5 or cross out the factor if it is not applicable. They were encouraged to provide their comments and suggestions at the end of the questionnaire.

The factors grouped under design documents are standardization of designs, simplicity, coordination between design documents, completion of design documents, clarity of specifications, underground construction, and specified tolerance. Standardization refers to the repetition of designs, which is to repeat the design details and typical floor layouts. A standardized design can facilitate the work as the labors have improved their skills and productivity by performing the same task. Moreover, the formwork can be reused for both in-situ and precast work. Simplicity is about the design with uncomplicated geometry, layout and shape of typical floor buildings, uncomplicated building system and installation details. Complicated design requires additional labors and skills to perform the work. The design documents that are required to be coordinated include specifications, architectural drawings, structural drawings, MEP drawings, and interior design drawings. The dimensional coordination between these drawings is very important for work on site. Lack of coordination between these documents reflects the poor quality of design and will result in rework. The complete design documents include the documents the contractor gets from the owner in the bidding process. Clarity of specifications refers to the clear technical specifications for materials and construction processes. The construction of basement will increase the difficulty of construction due to the soft soil conditions in Cambodia, especially Phnom Penh city, and the lack of heavy construction equipment and technical skills for small contractors. Tolerance is the acceptable difference between the drawing and the actual constructed object. Tolerance should be specified for as many items as possible and be referred to the construction code.

Table 4.6 Factors Label, Factor Category, and Factor Name

Factor Label	Factor Category	Factor Name
F1	Design Documents	Standardization of designs
F2	Design Documents	Simplicity
F3	Design Documents	Coordination between design documents
F4	Design Documents	Completion of design documents
F5	Design Documents	Clarity of specifications
F6	Design Documents	Underground construction
F7	Design Documents	Specified tolerance
F8	Design for Available Resources	Availability of materials
F9	Design for Available Resources	Availability of machines and equipment
F10	Design for Available Resources	Requirement of manpower
F11	Design for Available Resources	Requirement of skill
F12	Flexibility	Alternative construction details
F13	Flexibility	Wide alternatives of materials
F14	Flexibility	Allowing innovative construction methods/techniques
F15	Flexibility	Allowing flexible construction sequences
F16	Design to Support Safety & Site Layout	Design to suit site conditions
F17	Design to Support Safety & Site Layout	Design to support transportation of labors and materials
F18	Design to Support Safety & Site Layout	Safe approach to work
F19	Design to Support Safety & Site Layout	Design to support safety
F20	Design to Support Safety & Site Layout	Allowing safe construction sequences

Resources for buildability consist of materials, machines, manpower, and labor skills. Materials and machines here refer on their availability from local suppliers regardless if they are imported or produced in Cambodia. Most of the construction materials, machines and equipment used in Cambodia are imported from abroad, especially from neighboring countries. The supply of materials will be a problem only when the local suppliers are out of supply. In this case the contractor needs to consider about the lead time of the materials. Manpower refers to the requirement of labors during the construction process. Construction techniques requiring less labors are more buildable because it is getting more difficult to hire construction workers. Labor skill is the ability or expertise of a labor to perform a particular task or operate an equipment. Building projects using simple installation process and know-how available locally can facilitate the construction process.

Buildability related to flexibility includes alternative construction details, wide alternatives of materials, allowing innovative construction techniques, and allowing flexible construction sequences. Alternative construction details refer to the adaptation of construction details according to the situation on site by the contractor without extensive rework. There might be some errors or conflicts in the design drawings that cannot be detected unless the actual construction is carried out. The construction process can be improved if the contractors are allowed to make some minor modifications of drawings. Alternative materials refer to the use of materials with the same performance in the specification. The buildability can be improved if the contractors are allowed to propose new construction techniques or arrange the construction sequences.

There are five factors related to buildability grouped under Design to Support Site Layout and Safety. The first is to investigate the site thoroughly for soil condition and underground structure, and design the building to suit the conditions on site. The second factor is related to design that support transportation of labors and materials within and to the site. Next three factors are related to safety during construction. Accidents on-site will interrupt the construction process and affect the morale of workers. Safe approach to work refers to the proper installation of scaffolding and its usage during the construction. Design to support safety refers to the features of permanent facility that can influence the safety of the constructor, for example, the design of temporary machines and equipment to anchor in permanent structures. The last factor is about the use of safe construction sequences and familiar construction techniques.

4.3 Analysis of Buildability Factors

The analysis of data in the first part of the questionnaire was done in three steps. The first is to check the internal consistency of the items in the questionnaire by using Cronbach's alpha. The second is to check whether these factors could be prioritized by using Kendall's coefficient of concordance (*W*). Finally, the importance of each buildability factor was determined by using one-tailed on-sample *t* test with the 3.5 cutoff score.

Table 4.7 Mean, Variance and Cronbach's alpha if Factor deleted

Factor Label	Factor Name	Scale Mean if Item Deleted	Scale Variance if Item Deleted	Cronbach's Alpha if Item Deleted
F01	Standardization of designs	75.51	71.90	0.742
F02	Simplicity	75.83	73.15	0.753
F03	Coordination between design documents	75.94	73.94	0.762
F04	Completion of design documents	75.60	71.60	0.742
F05	Clarity of specifications	75.60	71.31	0.741
F06	Underground construction	76.11	73.81	0.757
F07	Specified tolerance	76.54	69.84	0.753
F08	Availability of materials	75.91	69.14	0.737
F09	Availability of machines and equipment	76.06	69.06	0.737
F10	Requirement of manpower	75.97	71.97	0.748
F11	Requirement of skill	75.74	70.84	0.739
F12	Alternative construction details	76.26	70.49	0.749
F13	Wide alternatives of materials	76.37	69.36	0.747
F14	Allowing innovative construction methods/techniques	76.37	73.42	0.758
F15	Allowing flexible construction sequences	76.37	69.18	0.749
F16	Design to suit site conditions	75.74	66.26	0.721
F17	Design to support transportation of labors and materials	75.91	70.55	0.742
F18	Safe approach to work	76.20	63.99	0.721
F19	Design to support safety	76.23	66.36	0.730
F20	Allowing safe construction sequences	76.26	67.96	0.736

4.3.1 Reliability of Test

The value of Cronbach's alpha for this test is 0.753 which suggests that the scale has good internal consistency. The minimum recommended level of Cronbach's alpha is 0.7 according to Nunnally (1978). Table 4.4 shows that value of mean, variance and Cronbach's alpha if the factor is deleted from the list.

This table shows that individual value of all 20 items in the questionnaire does not have significant influence on the total samples' value of mean, variance and Cronbach's alpha. This implies that individual item measures the same latent variable, the buildability, on the same scale with the same degree of precision, but with different amount of errors (Graham, 2006).

4.3.2 Concordance Analysis

The value of Kendall's coefficient of concordance of this test is 0.084. The low value of *W* enables the rejection of the null hypothesis that the respondents' ratings are unanimous. Therefore, we can conclude with confidence that there is a lack of concordance among the 35 respondents which implies that the responses collected could be regarded as essentially random and the factors could be prioritized.

Table 4.8 Kendall's Coefficient of Concordance Test

Cases	Kendall's *W*	Chi-Square	DF	Significance
35	0.084	55.977	19	0.000

4.3.3 Importance of Buildability Factors

The 20 buildability factors are ranked by their mean values. The average mean of all buildability factors is 4.00. There are 10 factors that have their means above this value. All the factors evaluated have the mean values above or equal 3.5. Table 4.6 ranks the importance of the buildability factors in descending order of mean scores. The top 12 factors that affect the buildability of a design are (1) standardization of designs (mean = 4.51); (2) completion of design documents (mean = 4.43); (3) clarity of specifications (mean = 4.43); (4) requirement of skill (mean = 4.29); (5) design to suit site conditions (mean = 4.29); (6) simplicity (mean = 4.20); (7) availability of materials (mean = 4.11); (8) design to support transportation of labors and materials (mean =

4.11); (9) coordination between design documents (mean = 4.09); (10) requirement of manpower (mean = 4.06); (11) availability of machines and equipment (mean = 3.97); and (12) underground construction (mean = 3.91).

The data were further analyzed by one-tailed one-sample *t*-test. Table 4.7 indicates the perceived level of importance of the 20 buildability factors. All factors have the mean score equal or higher than 3.5. However, only 12 factors passed the level of acceptance greater than 95% (having the *p*-value less than 0.05). This means that their means are statistically greater than the 3.5 cutoff point and could be considered as significantly important factors in buildability evaluation.

Table 4.9 Ranking of Buildability Factors

Factor Label	Total Score	Mean	Std. Deviation	Relative Importance Index	Factor Rank	Weight (%)	Cumulative Weight
F01	158	4.51	0.119	0.90	1	5.64	5.64
F04	155	4.43	0.125	0.89	2	5.53	11.17
F05	155	4.43	0.131	0.89	3	5.53	16.71
F11	150	4.29	0.133	0.86	4	5.36	22.06
F16	150	4.29	0.156	0.86	5	5.36	27.42
F02	147	4.20	0.158	0.84	6	5.25	32.67
F08	144	4.11	0.168	0.82	7	5.14	37.81
F17	144	4.11	0.158	0.82	8	5.14	42.95
F03	143	4.09	0.190	0.82	9	5.11	48.05
F10	142	4.06	0.158	0.81	10	5.07	53.12
F09	139	3.97	0.171	0.79	11	4.96	58.09
F06	137	3.91	0.166	0.78	12	4.89	62.98
F18	134	3.83	0.211	0.77	13	4.78	67.76
F19	133	3.80	0.196	0.76	14	4.75	72.51
F12	132	3.77	0.197	0.75	15	4.71	77.22
F20	132	3.77	0.188	0.75	16	4.71	81.94
F13	128	3.66	0.213	0.73	17	4.57	86.50
F14	128	3.66	0.183	0.73	18	4.57	91.07
F15	128	3.66	0.224	0.73	19	4.57	95.64
F07	122	3.49	0.230	0.70	20	4.36	100.00

Table 4.10 Result of One-Sample *t* Test of Mean Score of 20 Buildability Factors

Factor Name	Factor Label	Mean	*t*-test (*p*-value)	Inference
Standardization of designs	F01	4.51	0.000	Important
Completion of design documents	F04	4.43	0.000	Important
Clarity of specifications	F05	4.43	0.000	Important
Requirement of skill	F11	4.29	0.000	Important
Design to suit site conditions	F16	4.29	0.000	Important
Simplicity	F02	4.20	0.000	Important
Availability of materials	F08	4.11	0.000	Important
Design to support transportation of labors and materials	F17	4.11	0.000	Important
Requirement of manpower	F10	4.09	0.002	Important
Coordination between design documents	F03	4.06	0.001	Important
Availability of machines and equipment	F09	3.97	0.005	Important
Underground construction	F06	3.91	0.009	Important
Safe approach to work	F18	3.83	0.064	Not Important
Design to support to safety	F19	3.80	0.067	Not Important
Alternative construction details	F12	3.77	0.089	Not Important
Allowing safe construction sequences	F20	3.77	0.079	Not Important
Wide alternatives of materials	F13	3.66	0.233	Not Important
Allowing innovative construction methods/techniques	F14	3.66	0.198	Not Important
Allowing flexible construction sequences	F15	3.66	0.244	Not Important
Specified tolerance	F07	3.49	0.475	Not Important

These factors are (1) standardization of designs (sig. 1-tailed = 0.000); (2) completion of design documents (sig. 1-tailed = 0.000); (3) clarity of specifications (sig. 1-tailed = 0.000); (4) requirement of skill (sig. 1-tailed = 0.000); (5) design to suit site conditions (sig. 1-tailed = 0.000); (6) simplicity (sig. 1-tailed = 0.000); (7) availability of materials (sig. 1-tailed = 0.000); (8) design to support transportation of labors and materials (sig. 1-tailed = 0.000); (9) requirement of manpower (sig. 1-tailed = 0.001); (10) coordination between design documents (sig. 1-tailed = 0.003); (11) availability of machines and equipment (sig. 1-tailed = 0.004); and (12) underground construction (sig. 1-tailed = 0.007).

4.4 Current Buildability Concepts in Cambodia

The structured interviews of 35 respondents in the main survey were transcribed and subjected to iterative analysis. First, the data collected were sorted and the meanings of the buildability factors are explored. Then the findings from different respondents were compared and contrasted to search for conclusion.

4.4.1 Standardization of Designs

The first perception of the respondents toward the word standardization was about the standard of design for structural components, for example the Building Code Requirements for Structural Concrete (ACI 318M-11) and Commentary, Eurocode 2: Design of concrete structures, or British Standard: Structural use concrete. Since Cambodia does not have a national standard for design of structural components, the designers can follow any standard to design the building structure and request for the approval from the Ministry of Land Management, Urban Planning and Construction, Cambodia. The contractors stated that the most commonly used standards of design by local designers are the American standard, European standard and British standard. But the foreign designers could use his own country's design standard. Therefore, the contractors needed to adapt to the standards from one project to another. These standards could be Japanese standard, Chinese standard, Korean standard, Thai standard or Vietnamese standard.

After explaining the meaning of standardization in this study, which is about the repetition of design details and floor layouts, the contractors thought that the designers had these concepts in their design and agreed that the standardized design could facilitate the construction process through repetitive use of formwork, less supervision of labors, reduced chance of error, and ease in making the shop drawings and as-built drawings. They argued that standardization of designs also facilitates the design and checking process of the designer. But the contractors also understood about the requirements of the client on aesthetics and functions of the buildings. They explained that a building design without standardization for the first floor is commonly accepted in Cambodia. For second floor and above, the floor layout should be kept the same. They suggested that the variation of the percentage of reinforcement in the column instead of the size of the column could also facilitates the work.

In conclusion, standardization of drawings and clarity design standard for the project were important for buildability improvement.

4.4.2 Simplicity

Simplicity of design concerns about the geometry of building components, the layout and shape of building. The respondents stated that although a simple architect design could facilitate the structural and MEP design and influence the construction process, simplicity was not their main concern. The design could be complicated if it is the client’s requirements.

Since most of the buildings in Cambodia are cast-in-situ concrete structures, the contractors can customize the shape of the building according to the design even if it requires more labors. Rectangular is considered as the most buildable shape. The respondents claimed that a building with rectangular shape, rectangular openings, rectangular building components, the same span length, and flat floor level is considered as simple design. Nevertheless, some of the respondent argued that the shape and layout of building also depend on its functions and purposes. They gave an example that for shopping center or symbolic building, attractive shape to catch the attentions of customers and visitors was more important than buildability. However, based on the interviews, most of the mid and high-rise buildings in Cambodia are of rectangular shape.

4.4.3 Coordination between Design Documents

Based on the interview, the design process in Cambodia starts when the client finds the designer to do the feasibility study of the project. After discussion between the designers and clients, the designers translated the requirements of the clients to develop several conceptual designs. The clients will choose and modify one conceptual design. The designers will develop more details of this conceptual design and get approval from the client to finalize in the design development phase. This architect drawings are then passed to the structural designers to calculate the structural components. The finished structural designs are then checked by the architect to assure the coordination with architectural designs. Next, the MEP engineers will design the mechanical devices, the wiring of electrical and plumbing system based on architectural and structural designs. Any modifications in one of these three designs needs coordination and communication with each other. The structural engineers and MEP engineers will prepare the structure and MEP technical specifications.

The respondents suggested that before submitting the final design documents to the clients, all of the architects and engineers involved should review these documents together to assure the coordination. If there are interior and landscape designers, they should also be included in the design review meeting. Based on the interviews, most of the coordination and reviewing processes in Cambodia are done manually in CAD files instead of BIM files. Therefore, these designs are prone to human mistakes. For example, if the changes in architectural designs are not clouded out in the drawings, the structural and MEP designers can easily overlook the changes and will result in conflicts between the drawings. The coordination can get worse if the designers of each drawing are in different companies which is normally the case.

4.4.4 Completion of Design Documents

The respondents suggested that complete design documents from the designers for the whole project should include architectural drawings, structural drawings, MEP drawings, technical specifications for each drawing, and the calculation notes. They stated that the completed design documents from the beginning of the project are very important to ensure that the construction process will not be interrupted by the delays of designs. They claimed that in Cambodia, for major projects, the owners prefer to parallel the design and the construction process to reduce project duration. In such projects, the owner divides the project into several phases, and release the drawing of each phase for contractors to bid. Normally, the owner will make a lump sum contract with the contractor for the parts that have clear drawings and quantity, and a unit price contract for works that are unclear and subject to change. The respondents believed that by dividing the project into smaller parts, the owner has more financial flexibility to complete only parts of the project to supply the market demands and to reduce the expenses on detailed designs that are not built in the current phase of project. Therefore, the completeness of drawings depends on the scope of work responsible by the contractors in different phases.

4.4.5 Clarity of Specifications

The respondents explained that specifications were very important for contractors to estimate the bidding price and to make the method statement of construction. They are tools of coordination between consultants, designers and contractors regarding the inspection and the acceptance of works. Each project should have specifications customized for the project requirements, but the contractors in Cambodia claimed that many specifications they encountered are “copy and paste” from one project to another. Therefore, some parts of the specifications in such projects were not necessary while the other part were missing.

Based on the interviews, the designers explained that they had general specifications for all projects of the same type and they would modify them according to the project. The contractors stated that the important point of specifications was to clarify the requirements of the materials used, the methods to use the materials and machines, and the requirements of the work quality. The local designers stated that they would only specify the performances of the materials and try to make sure that the materials used in the specifications are available from at least two local suppliers and will put the word “or equivalent” at the end of the specifications of the materials. Some contractors explained that sometimes they had difficulty in finding the products in the specifications since the foreign designers did not consider about the availability of the materials and equipment in Cambodia market.

In terms of materials specifications, the contractors showed that they preferred performance specifications to detail specifications because they would have more flexibility to propose the substitutions. The contractors would choose a specific product to put in the bill of quantity in the bidding documents. For technical specifications, the contractors proposed that the designer should follow a specific design standard so that they had a reference to prepare the method statement and to clarify the ambiguities in the designs. The general notes and the typical drawings should be clear and followed a specific design standard. They should be included in the specifications. Generally, Cambodian designers follow the American or the European standards to prepare the specifications for materials and detailing. The respondents stated that the most commonly used standard in Cambodia were the publications of the American Society for Testing and Materials (ASTM), American Concrete Institute (ACI), American Institute of Steel Construction (AISC), British Standard Institution (BSi), and European Committee for Standardization (CEN).

4.4.6 Underground Construction

The respondents suggested that the construction of building space below soil level as a car park was getting popular in Cambodia in recent year as the population grows and the land price in the city increased. They reasoned that the high water level and the soft soil conditions found throughout the city increased difficulty for excavation. Moreover, since there are raining and dry season in Cambodia, they suggested all the underground works should be finished within the dry season or the rain would greatly increase the difficulty and might delay the whole construction schedule.

The respondents explained that the normal method to build the basement was cut the soil in open space without any support and covered it after the construction. However, under limited site space, sheet pile, diaphragm wall, micro pile, bored pile or precast pile was used and the effect of excavation on surrounding building must be considered. Only some major contractors among the respondents own the equipment and skill to perform these works. Most of the respondents have to rent the machines and equipment from the suppliers or subcontract the works. The respondents claimed that skilled and experienced engineers and workers for basement construction were difficult to find in Cambodia. Therefore, currently, the basement is mostly constructed in large projects that have large construction space. In addition, some respondents suggested that the basements need to be large enough to achieve economies of scale.

Some respondents stated they would choose to avoid underground construction, but the final decision was depended on the owners. They argued that the main factors that push the project owner to build basements were the desires to use the valuable ground floor as commercial area, such as bank or shopping center, to have larger parking space, and to gain enough commercial floor area under the regulations on building height. The depth and the number of floors of basement varied according to the demand of the owners, but semi-underground below the ground floor seemed to be a compromise solution to facilitate the work. As the city expands, the contractors expect to have more and more projects with basements.

4.4.7 Tolerance

Tolerance refers to the difference between drawings and actual building components. It is a very important document to check the quality of the work of the contractor. Unclear specifications can be the source of conflicts between consultant and contractor. Despite its importance, the respondents stated that it was rarely mentioned in the design drawings and specifications in Cambodia. They claimed that only in the designs with high standard that the tolerance for most of the building components were clear. The respondent stated that even if the tolerances were listed in the general notes, more clarifications for each specific case were still required.

Normally, the contractors will discuss about the requirements of the completed works with the consultant before performing them. Some contractors did not consider the tolerance as an important part of the design documents. The requirement of tolerance depends on the consultants. The errors of 2 to 3 millimeters are consider acceptable for strict consultants. For normal consultants, the errors less than 5 millimeters are generally accepted. The errors more than 10 millimeters require further discussion between the consultants and the contractors. The contractors also reasoned that more tolerance should be given according to the size, type and complexity of structure. The contractors preferred tolerance in number to the tolerance described in text. Nowadays, some contractors use laser devises to increase the precisions of verticality and horizontality of building components.

4.4.8 Availability of Materials

Based on the interviews, most of the construction materials in Cambodia are imported from Thailand, Vietnam, China and other countries in Asia. The local construction materials that can satisfy the local demand are sand, aggregate, brick, small wood support, and unprocessed wood board. There is only one cement factory in Cambodia and the production is not enough. Other commonly used construction materials such as steel reinforcement, cement, formwork, scaffolding, and cable are imported. The contractors stated that they could purchase most of the construction materials from local suppliers and order special materials from abroad if needed. Materials for reinforced concrete structure could be easily found in Cambodia, but some special orders might be needed for other types of structures.

The contractors will try to find the materials specified in the contract documents from local suppliers first before searching the overseas suppliers. The respondents stated that they would try to use the product with the same name in the design documents available locally, then try to find the product with the same performance available locally, and finally import the product from abroad themselves. The contractors will import the materials if the required volume is large enough.

4.4.9 Availability of Machines and Equipment

The respondents claimed that all the construction machines and equipment used in Cambodia are imported, some of them are available from local suppliers and some others need special orders. Construction equipment for reinforced concrete structure, bored pile and driven pile are abundant in Cambodia. Concrete batching machines, tower crane, mobile crane, excavator, bulldozer, bore pile machines with diameter from 600 mm to 1500mm, diesel hammer, and vibratory hammer for steel sheet pile can be bought or rented from local suppliers. Some other equipment for post tension, steel and composite structure and spun pile, such as jacking machines, steel stud welding machines, spun pile compression machines, are more difficult to find and might need to be specially ordered from local or foreign suppliers.

The respondents stated that previously, due to limited capital and options, they needed to rent or buy used construction equipment, especially from Japan, U.S.A., and Korea. But nowadays, as the Chinese equipment suppliers enter Cambodia market, they preferred to buy or lease brand new and cheaper Chinese equipment from local dealers. Some special equipment could also be easily ordered via local representatives of equipment suppliers.

4.4.10 Manpower Requirement

Cambodia has a very young population distribution, 44 percentages of its population age between 20 to 54 years old and another 45 percentages are under nineteen (MEASURE DHS, 2011). Despite the numerous people in working age, the contractors are complaining about the difficulty of recruiting construction labors. There are three main reasons, first many young men and women with enough initial capital would pay the recruitment agencies to work in South Korea, Malaysia or Thailand in seeking for higher wages. Second, most of the low skilled workers in Cambodia are migrant workers who are farmers during the harvesting season, but at other times, work as construction workers. Therefore, the supply of construction workers is not stable. Third, there were many new construction projects launched in the last two years, especially the major projects in Phnom Penh city. These factors make the contractors compete for construction workers in local and international markets. Many small and medium contractors would not maintain a large construction crew, but keep only the core skilled labors. They would subcontract some works to the external headworkers or recruit additional workers when they get a new project. It would not be economic for them to keep many workers if they cannot provide the workers the jobs continuously.

In addition to Cambodian workers, the respondents noticed that there are also many Vietnamese workers in Cambodia. They come to work in Cambodia, especially for Vietnamese construction companies, without any requirements of legal permissions and ask for similar wages to Cambodian workers. Some of the respondents also recruit Vietnamese workers, directly and by subcontracting. Nowadays, the contractors have recognized labor supply as one of the main issues in construction and try to use construction techniques requiring less labors.

4.4.11 Requirement of Skill

Some respondents claimed that Cambodia is not only in a shortage of construction workers, but in a great shortage of skilled construction workers because construction is perceived as a dangerous and laborious job in Cambodia. Most workers, especially female workers would rather go to work in the garment factories than in the construction sites. Moreover, there are very few technical training schools in Cambodia, and none of them teaches about the basic and practical skills related to construction, such as installing scaffolding, formwork, or operating heavy equipment. Some respondents stated that their workers have to work as an apprentice for the experienced construction worker on site to learn necessary skills. Most of the skilled workers are only skillful in reinforced concrete work since other types of structures are new to them. The contractors stated that only about 20 percentages of self-claimed skilled labors are really skillful, and they are only skillful in some particular tasks. Workers with many skills are very difficult to find in Cambodia.

To solve this problem, some Vietnamese companies bring the Vietnamese workers to work with Cambodian workers and suggest that the Vietnamese workers are more skillful and hardworking than the Cambodian workers. Some of the respondents who are local construction companies also have some informal on-the-job trainings for the new and unskilled construction workers who need more supervision and instructions. Some contractors suggested that more technical training schools rather than engineering schools should be established.

4.4.12 Flexibility to Changes

There are four buildability factors under flexibility to change: alternative construction details, wide alternatives of materials, allowing innovative construction techniques, and allowing flexible construction sequences.

The contactors stated that the designers would provide only one type of design details and they would develop construction or shop drawings based on the design drawings. These construction drawings of the contractors required approval from the consultant before the construction. The drawing details from the designer could be changed only if the client asked the designer to change, or there were mistakes in the designs, or the details were too difficult to construct that the contractor proposed a new detail or asked the designer to give a new detail. The contractors could not change the details of design drawings without the approval of the consultant, but they could propose new details based on actual situations. Some contractors stated that it would facilitate the construction processes if the designers allowed the contractors to adapt the drawings to the actual construction situations on site to solve some minor design issues. These issues could be the conflicts between opening, rebar and cable, the change of rebar diameter with the same percentage of reinforcement, the change from using splicing to couple or welding, the change of stirrup type, the change of beam-column, beam-beam, or column-column connection type.

The contractors suggested that for structural materials such as concrete and reinforcing steel, the designer should specify only the performances of the materials. For other structural and architectural materials, the designer should specify the names and performances of the materials. In both cases, the contractors need to propose one specific product in the bidding documents and use it for the construction. Therefore, allowing use of a wide range of materials could facilitate the contractors to choose the products during the bidding process. The contractors stated if there was the specific product name in the design documents, the contractors could use it without extensive check by the consultant. However, if the selection of product was based on performance, then the products were required to be tested at each time of purchase. As a result, the contractors prefer a product with specific name and try to procure it from the local and foreign market before proposing an alternative product with equivalent performance. Some local suppliers also provide training to teach the contractors to use their products. In some projects, the contractor would be responsible to supply the structural materials and the owner would be responsible to supply the architectural materials to reduce the conflicts. In this case, the owner will compensate the contractor if the work is rejected due to poor material supplied, but the contractor will compensate the owner for the materials and rework if the work is rejected due to poor workmanship. Some contractors think that providing alternatives is not important, but making sure that the products are available from local suppliers is more important. The special cases of alternative materials are to increase the strength of concrete to shorter the curing time and to increase the strength of rebar to reduce the percentage of reinforcement. The respondents stated that some consultants might not agree with these practices, but they believed that the designs that allow these practices could facilitate the construction process.

The selection of construction techniques is the result of consideration between time, cost, and available resources of the contractors under the given design drawings. Large span structure would require post-tension or steel structure, fast track structure would require partially or fully prefabricated structure. In Cambodia, the contractors stated they had full responsibility and freedom to select the construction techniques as long as they were in accordance with the design documents. The construction techniques used in the project were proposed in the method statement. The contractors could propose innovative construction techniques and change the design, but in this case the contractors would be responsible to design the proposed parts, although it was not a common practice. Normally, the contractors would follow the given design if there was no major difficulty to construct. Since the construction techniques are greatly restricted by the design drawings, the designers should consider about contractors' suggestions and experience in the conceptual design stage before developing the detailed designs. Based on the interviews, most Cambodian contractors still used traditional scaffolding and formwork for reinforced concrete mid-rise structure, other types of formworks, such as table formworks or slip formworks are still new to them. The post-tension and prefabricated structures are not yet popular. But the contractors start to realize the benefits of the innovative construction techniques. Some major contractors are using the post-tensioning structure with table formwork and partial onsite precast components. Some small contractors are also preparing to acquire new construction techniques and skills. In some projects, if the design requires the techniques that the contractors do not have, the contractors would subcontract this part of works or hire an expert to teach them.

The decision of construction sequences is based on project schedule and cost. The normal construction sequences of the building structure are bottom-up while the sequences of the architectural work are top-down. But when the schedule is tight, the structural and architectural works might overlap. The sequences for structural works do not have many variations since the contractors have to do according to the technical specifications. However, the construction sequences for the architectural works are more flexible. The contractors stated that they are generally responsible to prepare and adjust the construction sequences based on actual site progress and request for approval from the consultant. Normally, the designers do not fix the sequences of the construction work. Some contractors claimed that dividing the building into several parts or zones could facilitate the construction process since they had more flexibility to mobilize the construction resources from one zone to another when that particular zone was required to be reworked or the design of that zone was delayed.

4.4.13 Site Layout and Construction Safety

Construction site layout affects the efficiency and the safety of the construction process as a whole. As a common practice, the contractors are responsible to arrange the site layout based on the given site conditions and building location, and request for approval from the consultant before the commencement of the project. The design drawings are the input for the contractors to develop the construction site layout. The designers will investigate the site and soil conditions and design the building to suit the given conditions. Thorough site investigation is not only important to design the foundation but also to eliminate the unexpected encounters of underground objects, such as existing foundations, pipelines, electricity lines, sewage or septic tanks, during construction. The excavation on the pipeline and electricity line is very dangerous for construction workers and would also disturb the normal operation of surrounding buildings. Some respondents reported their experienced of change in foundation design during the construction due to poor soil investigation.

Free space on construction site directly affects the selection of construction techniques, storage and supply of materials and equipment. The respondents stated that the construction difficulty increases as the proximity to the surrounding buildings increases. For example, they can use cut and cover method instead of steel sheet pile or diaphragm wall to build basement if the site is large enough. Small site area also prevents the contractors from using on site prefabrication and heavy equipment, and storing enough materials.

Transportation of a construction project can be divided into transportation from the suppliers to the construction site and the transportation of the warehouse on site within the working area. The contractors stated they would be responsible for both on- and off-site transportation, and try to prevent the traffic jam and the accidents on pedestrians. The contractors explained that the designers would only consider about the transportation problems related to handling of structural elements that they design, site access of hazardous working area or extension of existing building. The contractors stated off-site transportation problem of oversize equipment or materials could be solved by requesting for traffic control of public road or by transferring the responsibility of transportation to the suppliers. On-site transportation problem could be settled by installation of tower crane and elevator. Therefore, it is very important that the building designs allow the contractors to install a tower crane that could cover the whole site area. Some contractors pointed out that temporary disturbance of public roads in urban areas, especially the major boulevards, required special permission from the local authority.

Safety is the top priority for construction projects. An accident on site affects the morale of workers and the reputation of contractor, consultant and owner. The investigation of the accident could jeopardize the construction process and delay the schedule. The perception that the contractor is the sole party responsible for safety is deeply ingrained in the Cambodian construction industry. This is due to the fact that the contractor is the party that actually execute the work. But this perception is not totally correct, a study of construction safety indicates that 42% of fatalities reviewed were related to the design concepts (Behm, 2005). The consideration of construction site safety in the design of a project could have improved the worker safety.

Based on the interviews, the contractors in Cambodia considered safety as their management problems and agreed to assume the responsibility. Based on the design drawings, the contractors plan the access route to the working area and the emergency exit. For working at height and outside the building, the contractors would install the scaffolding, safety belt, safety and dust net. The contractors are also responsible to install lighting, guardrail, fire extinguisher, standard procedure for accidents, and employ safety engineers on site. However, the emphasis on safety also varies depending on consultant, contractor and project manager. Foreign and large standardized companies would concern more about safe approach to work than small local companies. Some local companies even claimed that they did not have enough budget to enforce the safety on site. These companies also claimed that the construction cost would increase if they were too strict on safety implementations.

Since there is no regulation about construction safety in designs, the designers do not have to consider about the installation of temporary equipment to support safety as well as the construction process. They are also lack of knowledge and experience to design for safety without applicable standards, codes of practices, and input from the contractors.

The contactors stated that they had to foresee the anchorage points for safety tools erection as well as the sequences of work that would enhance the safety during construction. Some contractors suggested that in fact the accidents could be prevented by designs that had less work at height and outside of the building. Examples of such are changing the shear wall from the edge to the interior of the building, changing the plastered wall to curtain wall. But the designers and contractors in Cambodia would consider these as architectural issues and design requirements of the client.

4.5 Conclusion

This chapter assesses the importance level of buildability factors from the perspective of contractors. First, the reliability of the questionnaire using the 5-point Likert scale was examined by Cronbach's alpha. Then the concordance of sample ranking sets was verified through Kendall's coefficient of *W* to assure that the answers of the respondents are random. After that the factors were ranked by their means. Finally the importance level of the buildability factors was tested using one-tailed one-sample *t*-test with the 95% level of confidence.

The results show that the factors related to design documents are considered as the most important contributors to facilitate the construction process. This reflects the fact that the contractors encounter many problems during construction caused by design documents. The resources were the next concern of contractors. The contractors are experiencing the difficulty to recruit construction workers, especially the skilled workers, due to the fact that more and more labors migrant to work abroad and the lack of professional training school within the country. Although Cambodia imports most of the construction materials and equipment from neighboring countries and China, the contractors can easily procure most of the necessary products from local suppliers or directly import from overseas. Factors related to flexibility to changes are of less concern because the contractors will follow the drawings and instruction of the designers and consultants without any suggestions. The changes after bidding could be claimed as variation order. Site conditions will affect the overall arrangement of site layout, the selection of construction techniques, the process of construction, and the productivity of the project. Although the main responsibility of construction safety falls on the contractors, the factors related to safety are not the top concerns of contractors during the construction since there is no clear regulation about construction safety.

The overall ranking and ranking within each category of buildability factors provide useful information for designers to improve buildability of their design. The important factors of this research are used for further development of buildability assessment model for building construction in Cambodia.

CHAPTER V
DEVELOPMENT OF BUILDABILITY ASSESSMENT MODEL

The development process of an AHP model to assess the buildability of building designs is elaborated in this chapter. This model is structured on the important buildability factors identified in chapter 4. The buildability is assessed based on the 12 factors under three categories. The judgments of 28 respondents were aggregated to obtain the relative weights of the buildability factors. The assessment mechanism, the results, the scale, and the subcriteria to evaluate each buildability factor of the model are discussed in the last part of the chapter.

5.1 Description of Data Collection

The data used in this chapter are the answers of the second and the third part of the main questionnaire, and the first part of the validation questionnaire. There were 28 complete samples collected from the second part of the main questionnaire used for the development of the buildability assessment model. Ten respondents of the first part of the validation questionnaire contributed their knowledge about the subcriteria and the details of subcriteria to evaluate the buildability factors.

The respondents of the validation survey were selected among the respondents of the main survey to ensure that they understood the subject matters and to improve the consistency of their answers. The validation survey was conducted from June15 to 29, 2014. In addition, a complementary survey from September 7 to 14, 2014 was conducted to verify the weight of the buildability criteria.

Before asking for the subcriteria and the details to evaluate the buildability factors, which was the first part of validation questionnaire, the objectives of the questionnaire were explained and the examples of the subcriteria to evaluate the buildability factors were given to the respondents to elicit their responses.

5.2 Structure of the Model

The questionnaires were distributed to the project engineers, the project managers, and the directors of mid- and high-rise building project contractors. Twentyeight complete questionnaires were collected back. The consistency of the answers of each respondent as well as the consistency of the group's answers was checked.

Table 5.11 Label, Category, and Name of Important Factors

Factor Label	Factor Category	Factor Name
F1	Design Document	Standardization of designs
F2	Design Document	Simplicity
F3	Design Document	Coordination between design documents
F4	Design Document	Completion of design documents
F5	Design Document	Clarity of specifications
F6	Design Document	Underground construction
F8	Design for Available Resources	Availability of materials
F9	Design for Available Resources	Availability of machines and equipment
F10	Design for Available Resources	Requirement of manpower
F11	Design for Available Resources	Requirement of skill
F16	Design to Support Site Layout	Design to suit site conditions
F17	Design to Support Site Layout	Design to support transportation of labors and materials

The important factor categories and the factors (see Table 5.1) correspond to the criteria and the subcriteria in level 2 and 3 used in the AHP model (see Figure 5.1). The level of importance of the buildability factors was evaluated by one-sample *t* test in Chapter 4. The criteria in level 2 are design documents, design for available resources, and design to support site layout. The subcriteria under design documents are standardization of designs, simplicity, coordination between design documents, completion of design documents, clarity of specifications, and underground construction. The subcriteria of design for available resources consists of materials, machines and equipment, manpower, and skill. Design to suit site conditions and design to support transportation are the subcriteria under design to support site layout. The answers of AHP pairwise comparison of Respondent PM5 are shown in Table 5.2 in the form of a matrix as an example. The table shows only the values of the upper triangular matrix since the values of the lower triangular matrix are the inverted values of the corresponding upper triangular matrix.

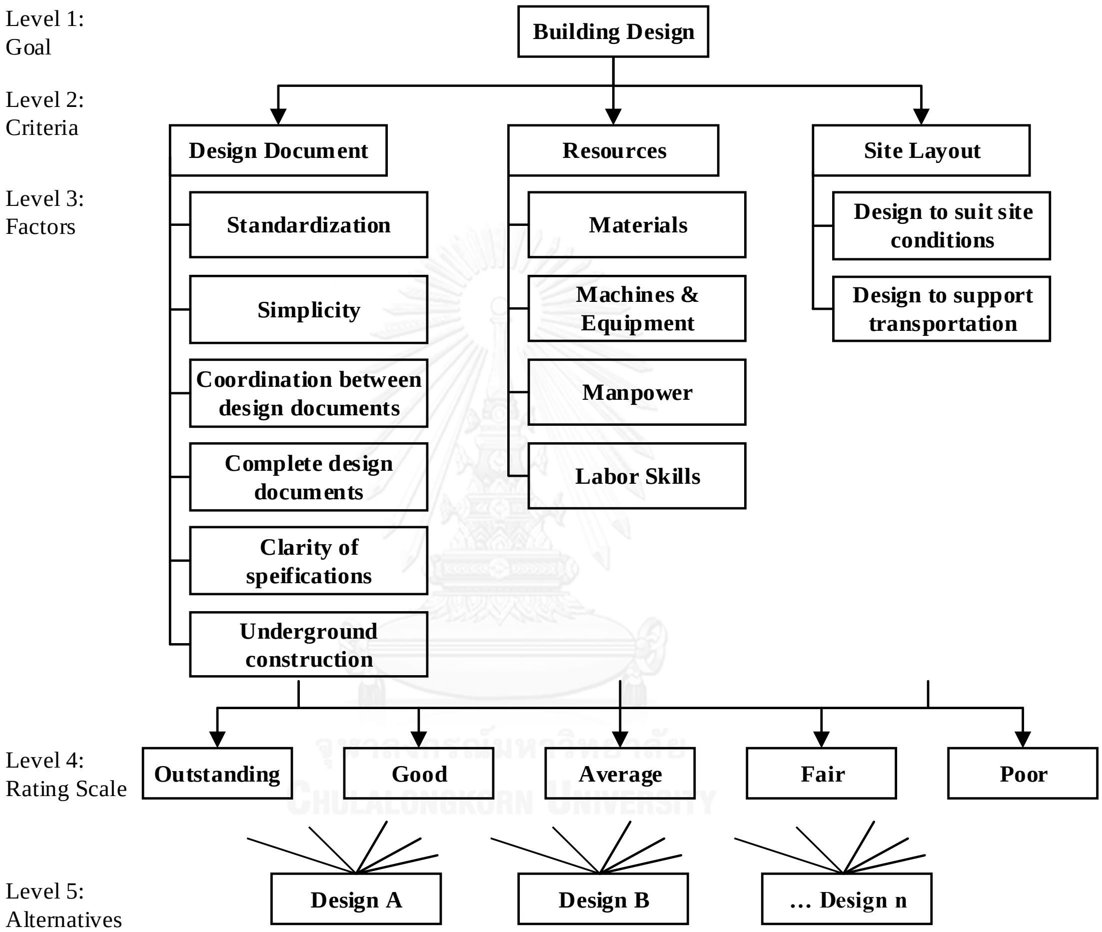

Figure 5.9 AHP Hierarchy Structure of Buildability Assessment

Table 5.12 Pairwise Comparison of Respondent PM 5

Buildability

	Design	Resources	Site Layout
Design	1	5	1/3
Resources		1	1/5
Site Layout			1

Design Documents

	Standardiza-tion	Simpli-city	Coordina-tion	Comple-tion	Specifica-tions	Underground construction
Standardization	1	5	1/9	1/5	1	1
Simplicity		1	1/9	1/5	1/3	1/3
Coordination			1	9	9	9
Completion				1	5	5
Specifications					1	3
Underground construction						1

Design for Available Resources

	Materials	MACH & EQPMT	Manpower	Labor Skill
Materials	1	1/3	1/5	1/7
MACH & EQPMT		1	1/7	1/7
Manpower			1	1
Labor Skill				1

Design to Support Site Layout

	Suit Site Conditions	Support Transportation
Suit Site Conditions	1	1/5
Support Transportation		1

5.3 AHP Data Analysis and Results

The pairwise judgments of the 28 experts were combined by the geometric mean at each level of the AHP structure and then put into the pairwise comparison matrix. The local weight of each element in respective level was derived and then aggregated from the top to bottom to obtain the global weights. Table 5.3 shows the pairwise comparison judgment matrixes of the buildability assessment problem from 28 respondents. The consistency ratio of the combined judgments in each level shown was below the recommended level of 0.1.

Table 5.13 Pairwise Comparison Judgment Matrixes after Aggregation

Goal	Design Documents	Resources	Site Layout	Priority
Design Documents	1.000	1.351	1.294	0.275
Resources		1.000	1.103	0.377
Site Layout & Safety			1.000	0.348
				CR = 0.00

Design doc	Standardize	Simplicity	Coordination	Completion	Spec.	Underground	Priority
Standardize	1.000	1.463	0.894	0.655	1.087	1.332	0.165
Simplicity		1.000	0.520	0.525	0.683	0.881	0.111
Coordination			1.000	0.864	1.162	1.422	0.193
Completion				1.000	1.940	2.113	0.249
Specification					1.000	1.852	0.164
Underground						1.000	0.118
							CR=0.01

Resources	Materials	Machines & equipment	Manpower	Labor skill	Priority
Materials	1.000	1.033	1.033	0.716	0.230
Machines & equipment		1.000	0.954	0.634	0.215
Manpower			1.000	0.664	0.223
Labor skill				1.000	0.332
					CR = 0.00

Site Layout	Suit site conditions	Support transportation	Priority
Suit site conditions	1.000	0.872	0.466
Support transportation		1.000	0.534
			CR = 0.00

The global priority weights were determined for all 12 important factors. Table 5.4 illustrates the composite priority weight of the buildability factors after aggregation. Design for available resources was the criterion that had the highest local weight followed by design to support site layout and design documents. The number of the subcriteria directly affects the weights shared by them. The subcriterion that had less siblings could share more weight comparing to the subcriterion that has more siblings.

As shown in Table 5.4, the buildability factors under site layout and safety had higher global weights than the factors under resources and design documents. The global priority weights of these buildability factors were then multiplied with the rating scale suggested by Liberatore, and summed together to get the buildability score of a design.

Table 5.14 Composite Priority Weight of Buildability Factors

Criteria	Local weights	Subcriteria	Local weights	Global weights
Design documents	0.275	Standardization of designs	0.165	0.046
		Simplicity	0.111	0.031
		Coordination	0.193	0.053
		Completion of design doc	0.249	0.068
		Clarity of specifications	0.164	0.045
		Underground construction	0.118	0.032
Resources	0.377	Materials	0.230	0.087
		Machines & equipment	0.215	0.081
		Manpower	0.223	0.084
		Labor skill	0.332	0.125
Site layout	0.348	Suit site conditions	0.466	0.162
		Support transportation	0.534	0.186
			Total =	1.000

Table 5.15 Ranking of Buildability Weights

Rank	Buildability Factors	Global Weights
1	Support transportation	0.186
2	Suit site conditions	0.162
3	Requirement of labor skill	0.125
4	Availability of materials	0.087
5	Requirement of manpower	0.084
6	Availability of machines & equipment	0.081
7	Completion of design doc	0.068
8	Coordination	0.053
9	Standardization of designs	0.046
10	Clarity of specifications	0.045
11	Underground construction	0.032
12	Simplicity	0.031
	Total =	1.000

5.4 Discussion about the AHP Weights of the Buildability Criteria

In order to verify the weights of the buildability criteria, additional data collection was conducted and detailed reasoning behind the judgments of each respondent were recorded and analyzed. Table 5.6 shows the result of the AHP weight of the buildability criteria.

The results of AHP weights of the buildability criteria for the first data collection (28 samples) are Design Document (0.275), Design for Available Resources (0.377), and Design to Support Site Layout (0.348). Another data collection (8 samples) was carried out to verify this result. The AHP weights of buildability criteria for the second data collection (8 samples) are Design Document (0.274), Design for Available Resources (0.331), and Design to Support Site Layout (0.395).

The AHP weights of the Design Document criterion for both data collection are similar, 0.275 and 0.274. However, the weight of Design to Support Site Layout slightly increases from 0.348 to 0.395, while the weight of Design for Available Resources slightly drops from 0.377 to 0.395. In general, the weights of the buildability criteria basically remain the same, although the ranking of the first two is reversed.

Table 5.16 Ranking of Buildability Weights

AHP Weights	First Data (28 Respondents)	Second Data (8 Respondents)
Design Document	0.275	0.274
Design for Available Resources	0.377	0.331
Design to Support Site Layout	0.348	0.395

The weight of Design to Support Site Layout is higher than the other two criteria because the site layout of a project imposes some restrictions on the construction processes. For building projects located in the center of the city and very close to the existing building, especially close to the hospitals or the high-ranking people, the projects would have difficulty working overtime during night time. For projects located in special areas, such as an airport or next to an operating building, the contractors also need to foresee the potential conflicts of transportation and right of access. Moreover, the designers and the contractors also need to consider about the effects of the construction process, such as noise and vibration, on the neighbors. The vibration or the excavation of the foundation and the basement may cause the surrounding building to crack, incline or slide, which will result in conflicts and litigations. For projects with small site area, the contractors also need to purchase the materials more often, and pay more attention to management of working area, reallocation of temporary facilities, and accommodation of the workers. For projects located in rural areas, the contractors will have additional difficulty to recruit the workers, and need to pay higher wages, and be responsible for their accommodation and food.

The problem of available resources is another important issue. Since many construction materials in Cambodia are imported, the contractors need to foresee the lead time and the risk of materials delays. This problem is less severe if the specifications of the materials are clear and flexible. The contractors will have sufficient time to respond or propose for alternative materials. However, changes of designs during the construction are very difficult to avoid given the current practices. The specifications are usually unclear and also subjected to changes, especially for architectural and MEP works approaching the end of the project. At this stage, many tasks become critical and the problem of unavailable resources will be crucial. Therefore, the contractors give higher priority to the resources over the design documents. Some respondents view the site layout as "a given resource" and other resources determined by the design documents as "controllable resources". This might be the reasons that these two criteria have similar weights.

When the contractors evaluate the design documents, they not only consider about the difficulty of construction of the drawings, but also about the potential management problems caused by the designs. For designs that are difficult to construct or have unclear drawings, the contractors need to propose a new design and discuss with the designers during the construction. Moreover, since most of the building projects in Cambodia are cast-in-place and the cost of labors is relatively low, the problems of standardization and simplicity of designs are less critical. The Design Documents are not only the basis for construction, but they are also the results after the considerations of the available site area and the resources. An experienced designer will accurately collect the data of the site and the available resources, and use them effectively in his design. A good design will not only satisfy the project owner's demands, but also facilitate the construction processes at the same time.

The weights of the buildability criteria also reflect the current problems faced by the contractors. The contractors who were facing problems with resources would give higher weight on this criterion.

5.5 Difference between AHP Weight and Level of Importance

In AHP, the global weights of the buildability factors were determined by multiplying the local weights of the buildability factors with the local weights of the buildability criteria. The sum of the weights of all buildability factors under each criteria is 1.000. This means that the buildability factors in the group that has less elements (i.e. the criteria that has less factors) are more likely to get more global weight. The structure of the hierarchy of AHP has direct influence on the global weight of the factor.

Saaty (1987) pointed out that with relative measurement, rank changes with respect to several criteria only because of the structural dependence (involving both number and measurements) of criteria on alternatives. Choo et al. (1999) claimed that the criteria weights are not directly related to the discriminating power of the criteria in AHP by the partial value. Any top-down pairwise comparison of criteria relative importance will only yield arbitrary weight values (Barzilai, 1997, Barzilai, 1998, Barzilai, 2001, Dyer, 1990).

Therefore, the global weight from AHP could not be compared across different main ideas/groups. Only the factors under the same group can be compared in a meaningful way. On the other hand, the ranking of the level of importance is not made in group. Therefore, the ranks of the level of importance of the elements in the lower level are not affected by the ranks of the level of importance of the upper level.

5.6 Subcriteria to Evaluate Buildability Factors

There are 12 factors to evaluate the buildability of the design documents of a mid or high-rise building. The subcriteria to evaluate the buildability factors and the current practices of designs were derived from the cross-case analyses of 11 building projects in Phnom Penh city (see Table 6.1).

The subcriteria are important because they allow the evaluator to assess the buildability of a design in more detail. Moreover, the current practices of designs are considered by the respondents as the designs of average buildability. Since the user of the model needs to evaluate the buildability by using the Liberatore 5-point rating scale, the designs that are in accordance with the current practices can be rated as average. Therefore, the subcriteria and the current practices are the references for the users of the model to evaluate each buildability factor. The summary table of the subcriteria to evaluate the buildability factors and the current practices of designs to achieve such subcriteria are attached in Appendix B.

5.6.1 Standardization of Designs

There are five subcriteria to evaluate the level of standardization of a design. These subcriteria are repetitions of floor layout, repetition of floor height, repetition of building components, repetition of openings/block-outs, and design standard.

Based on the analysis, the layout of the ground floor is usually different from the other floors for common mid- and high-rise buildings. This is because the ground floor is normally used as a public area, such as lobby and reception. The layout of the basements is usually the same, but the floor layouts of the superstructure may vary according to different functions. For multipurpose buildings, the floor layout for each function should be the same. In any cases, the floor layout should be repeated for at least 2 storeys to achieve economic use of formworks. The floors next to the top may have different layout from the lower floors because they could be sold at a higher price. The design of the top floor or the roof is also different. Nowadays, some owners prefer to use the top floor as a relaxing area by constructing a swimming pool, a garden or a bar. For some types of buildings, such as shopping mall, theater or museum, the floor layout may be different for each individual floor to attract the customers.

The best practice of standardization would be that the floor layout above the ground floor is the same for every storey. On the other hand, the poor practice, which is not common, is that the layouts of the building are different for every storey. The roof is not taken into account.

Similarly, the height of the ground floor is usually higher than the other floors. For the storeys above the ground floor, the floor height should be the same for the floors serving the same function. The basement floors should also have the same height. The floor height should be repeated for at least 2 storeys to achieve economic use of formworks. The optimal height of a normal floor is between 3.3 to 3.5 meters. The best practice is that the floor height of the building varies only two to three times for the whole building, while the poor practice could be that the floor height varies many times, for instance more than 5 times.

The standardization of building components is divided into the standardization within the floor and the standardization between the floors. The standardization within the floor refers to the repetition of the sections of building components within each floor, while the standardization between the floors refers to the repetition of these sections in different floors. Four suggestions were derived from the interviews. First, there should be normally three types of columns for each floor, namely the interior, the exterior, and the corner or the perimeter. These sections should be repeated for at least 3 storeys to be buildable. Second, there should be at most three types of beams for each floor, which are the primary beams for both directions, the secondary beams for both directions, and the cantilevers. The beams for stairs and elevators should be considered separately. The sections of beams should be kept the same for the floors that have the same function. Third, the sections of concrete walls should remain the same for every floor regardless of its function. Last, there should be only one type (of structure) of floor for a single storey, but the thickness of an individual floor could be varied according to the design. The floor thickness for car park could be higher than the normal floor, while the post-tension floor is normally thicker than the reinforced concrete floor. The best practice is that the section of every type of building component is the same for every storey. However, it is not economical in practice. Therefore, two to three types of sections for each type of building components repeated for more than 3 floors are considered as designs with good buildability. In this case, there should be only one top and level bottom of the slab. For poor practice, which is rare, there could be more than three types of sections of columns, beams and walls due to uneven and non-repetitive gridlines of the building layouts, and the top and level bottom of the slab could also be uneven.

To achieve standardization of designs, most of the openings or the block-outs of the architectural and MEP designs of each floor should have the same dimensions and be kept at the same locations. The same concepts are applicable to architectural block-outs of slabs, such as indoor atrium patios, and walls. For poor practice, the dimensions and the locations of the openings and the block-outs may be different from one storey to another.

Since Cambodia does not have a national design standard for structural components, the use of the design standard depends on the preference of the designers and the owners. The most commonly used design standards in Cambodia are the British Standard (BS), the Euro Code, the French Standard (BAEL), and the United State standard (ACI, AISC). Normally, the owners or the designers prefer to use the design standard from their own countries. The contractors stated that they did not have difficulty to adopt to the new design standards as long as the design concepts were similar to the above mentioned standards. Therefore, the usage of the design standards depends on the experience of the contractors. In the general, the European and the American standard could be considered as common standards for most contractors.

5.6.2 Simplicity

There are three criteria to be considered under simplicity. They are the shape of building, the building components, and the openings and block-outs. Interestingly, some contractors consider that simplicity is not as important as standardization of designs in facilitating the construction process.

The most commonly encountered shape of the buildings is rectangular. Square is the easiest shape to be constructed. The shapes composed of rectangles, such as L shape or T shape, are considered as acceptable. The buildings with non-symmetrical shapes require more time and efforts to survey and make the formworks for the first time. Curved structure is more difficult to construct than straight structure. But once the formworks are made for one floor, it would be easy to replicate the same formworks for the following floors. But in some cases, such as iconic buildings or shopping centers, the attractiveness of the buildings is more important than the buildability, and therefore the shapes of the buildings could be complicated.

The same concepts are also applicable to building components. Rectangular structural components are easier to construct compared with the other shapes. Curved beams or inclined columns are not commonly encountered and they more difficult to build. It is difficult to make formwork, to pour concrete, and to assure the verticality tolerance for columns higher than 6 meters. For slabs, the bathroom and the balcony are usually 5 centimeters lower than the normal slab level, therefore the concrete could be poured in one time for each floor. The level top of the floors for a car park require a slope to drain water, but the level bottom of every floor should be kept the same. The buildability of a slab also depends on the types of structures. The difficulty of construction increases as followings: flat slab, slab with drop panel, slab with band beam, and reinforced concrete slab with beams.

The openings and the block-outs also affect the buildability of the building. All the openings and the block-outs should be made before pouring the concrete. Coring the concrete after casting is a time consuming process and it would also affect the integrity of the structure, and therefore it should be avoided. Round and rectangular are the most common shapes of openings which are also easy to make. The numbers of openings should be kept minimum by combining them together. Openings through beams and concrete walls should be made with precaution and be eliminated if possible. For huge architectural block-outs, such as indoor atrium patios, their shapes significantly affect the buildability. Complicated patio will consume a lot more time and labors than the simple one.

5.6.3 Coordination between Design Documents

The coordination between design documents can be checked by reviewing the design documents of different disciplines for the conflicts of designs.

In the interviews, the contractors suggested that the coordination between design documents should be checked by the designers of different disciplines before the submission to the owner for each design phase. The designers should make sure that their designs are in accordance with the owner's requirements and complied with local regulations. The most common method to assure the coordination is through meetings between the architect, the structural and the MEP engineers using paper drawings. However, the use of 3 Dimensional (3D) models and Building Information Modeling (BIM) can significantly increase the quality of review and help designers and contractors to visualize the finished buildings.

The contractors stated that they should also check the coordination between the design documents before bidding, at least before starting the construction. The coordination could be checked by overlapping, combining and comparing the architectural, the structural and the MEP drawings. The main points to of checking between the architectural and the structural drawings are building layouts (the perimeter and the symmetry of the building), gridlines, sizes of columns, heights of beams and ceilings, and locations of block-outs. The important points to be checked between the structural and the MEP drawings are locations of openings of slabs and beams, locations of pipes and wirings, levels of ceilings and pipes, slope of the pipes, and locations of pipes relative to walls. All MEP conduits should be invisible and embedded in walls and above ceilings. The essential points to be checked between the structural drawings are conflicts of space between structural components and users/devices (e.g. overhead space for walking and installing machines/equipment), space conflicts between cables and rebar, and conflicts between rebar and rebar. In addition, the coordination between drawings and specifications should also be checked. For example, for structural drawings and specifications of civil work, the points to be checked can be rebar dimensions, rebar laps, thicknesses of concrete covers, strength of materials, and standard detailing. The contractors also stated that they needed to make sure that the structural designs are strong enough before construction by checking the structural drawings and the calculation notes for potential errors of loads applied, modeling of structures, compliance with minimum requirements of the design standards, and adequacy of the designs of structural components based on their experience. The best practice would be that the coordination of design documents are checked by the designers of every discipline, and then double checked by the contractors using BIMs. Designs without a formal coordination review can cause problems during construction.

5.6.4 Completion of Design Documents

A complete set of design documents consists of drawing list, demolition plan (if applicable), architectural, structural, MEP, and interior drawings. The architectural drawings should include master plan, building layouts, perspective views, elevation views, and cross-section views of the building. The drawings could be divided into different parts, such as foundation, basement, superstructure, and architecture. However, the buildability will be improved if all drawings are finished before the commencement of the construction, and given to the contractors in one time. Designs in phases are usually associated with lack of coordination between the designs and may also impede the construction process due to the delays of designs.

5.6.5 Clarity of Specifications

The 4 criteria to evaluate the clarity of the specifications are scope of works, specifications of works and materials, tolerances, and general notes and typical details.

The scope of works should be included in the specifications and should be clearly defined for the responsibilities of owner, consultants, designers, contractors, and subcontractors (if applicable). It should also state about the definitions of the project, the budget of the project, the schedule of project, the site location and conditions, the general requirements, the allowance, the insurance, the warranties, the bidding process, the administration of project, and the process of conflict resolution.

Good specifications should be divided into different parts according to the disciplines, such as civil works, structural works, MEP works, and architectural works, and covered by the general specifications. For each part of the specifications, all requirements of the works and the performances of materials used in the drawings should be specified and be referred to the materials standards, for instance, ASTM, ISO, European Standard, or Chinese Standard GB/JGJ. Instead of using unclear alternatives by the word “or equivalent”, the specifications should mention the brand names, the origins, and the performances of the alternatives. For materials to be imported from abroad, the contact details of the suppliers should also be included. The methods to use the special materials should also be specified in the specifications in case there are many alternative application methods. The completeness of the specifications could be checked by comparisons with the drawings.

The tolerance of all works should be noted in the specifications. For structural works, the tolerance should be referred to design standards, such as ACI or Eurocode, so that the contractors could refer for more details themselves. The common tolerances of structural components include verticality of building, placements of reinforcements, covers of concrete, verticality of columns, deflections of beams and slabs, dimensions of precast members, placements of cables, prestressing forces, and dimensions and locations of openings and block-outs. The tolerance of architectural and MEP works should be included in the specifications and be noted on the drawings. Although tolerances of designs are very important references for acceptance of works and for dispute resolutions, it is usually ignored in the design documents.

General notes and typical details are important documents to complement the designs. The contractors could combine them with specific drawings to make shop drawings. General notes and typical details should be divided into different parts according to the disciplines. However, the designers should not rely on them so as to neglect the important details that should have been specified in the drawings. Typical details should be attached in front of the corresponding documents.

5.6.6 Underground Construction

The difficulty of the construction of underground structure depends on five criteria: groundwater, type of soil, surrounding buildings, location of site, and level of foundation. All these criteria affect the selection of construction methods, and therefore time, costs, and uncertainty of construction.

The most critical issue about the construction below soil level is the ingression of groundwater. If the excavation is carried out below the groundwater level, the contractors need to assure that the water is pumped out properly during the whole excavation period and to consider about the effects of the lowering water level and the extra settlements due to pumping on surrounding buildings. The influence of groundwater is even more significant if the site is located near the river or any natural or man-made water reservoirs. In these cases, the contractors also need to consider about the seasonal changes of natural water level on the underground water level of the construction site. The difficulty of the construction under the ground will greatly decrease if the groundwater level is below the excavation level.

Another factor that is closely related to groundwater level and also significantly affects the underground construction is the type of soil. For clay, it is not required to use some special treatments to stabilize the soil during the boring or the excavation. However, for poor soils, such as sand or mud, the contractors need to use chemicals to stabilize the soil during the boring process and to use soil retaining structures during the excavation. For very hard soil or stone, which are not common in Phnom Penh, the contractor also needs to make extra efforts for boring and excavating.

The distance from the surrounding buildings is an important criterion that affects the selection of construction methods. If the surrounding buildings are far from the building under construction, the contractor can use noisy and vibratory machines to work freely. But if the neighbors are close, the contractors need to use silent machines and work more delicately. On the other hand, the contractor can excavate the soil openly and do not need to retain the soil if the site boundary is at greater distance than the angles of repose of the soils. But if the space is small, the contractor need to use retaining structures, such as pole retaining walls, slurry walls, sheet piles, or bored piles, which take more time, skills, and money to construct.

The location of the site also affects the buildability of underground structures. For sites at downtown, the contractors need to clean the wheels' of the dump trucks and transport the debris to the dumping area only during the permitted time due to the traffic control regulations for heavy trucks in the city. But for sites in rural areas, the contractors can transport the excavated soil at any time.

The last criterion that influences the construction of underground structure is the lower level of the foundations. It would be easier to excavate the whole building area at the same level than to excavate the foundations at different levels. There might be problems of landslide if the depths of excavations are different. The problems are the same for the construction of basement. The basement with the same bottom floor level is easier to construct than the uneven one. For poor soil conditions, the designers can consider to use mat foundation, by combining the foundation and the lowest level of the basement, to strengthen the building and also to facilitate the construction.

5.6.7 Availability of Materials

Efficient material management is important to assure smooth construction processes. The main issue is the availability of the correct materials at the right time. The problems of using the materials not available locally are that the contractor needs to foresee the use of the materials in the construction schedule, order and make advance payment for these materials. These materials are also susceptible to the delays of delivery and the quantity changes due to inaccurate estimations and design changes.

For common materials of reinforced concrete structure, such as cement, sand, stone, and rebar, the contractors can get the supplies for less than two weeks. For other materials that are not common in the local market, but still available from some local suppliers, the delivery might take about one month. These materials include rebar with diameter greater than 25 mm, cables for post-tensioning, precast components, dry walls, curtain walls, and structural steel components. For precast components such as precast louvers, precast plain slabs and precast beams, the contractors could produce them on-site instead of order them from the manufactures. Since it takes about the same amount of time (two to three months) to import the materials from abroad, many contractors prefer importing the materials instead of purchasing them from local suppliers (given the quantity of materials could achieve economies of scale). In the case that the contractors are requested by the owners to use specific materials that are not available from local suppliers, the contractors will have to import these materials.

5.6.8 Availability of Machines and Equipment

Machines and equipment play an increasingly important role to improve the productivity of the workers. Major contractors prefer to import new machines and equipment from abroad because these contractors have sufficient financial resources and number of projects to achieve the economic use of the machines and equipment. Medium and small contractors prefer to rent or purchase the used machines and equipment. There are more and more international dealers of machines and equipment in Cambodia, from whom the contractors could rent, lease or buy their products. The availability of machines and equipment also depends on the popularity in local markets. The best sellers are available at any time of order since the dealers will reserve sufficient stock. For special machines or equipment, the lead time would take two to three months.

5.6.9 Requirement of Manpower

The factors that affect the requirements of number of workers at a given time are the types of structures and the schedule of works. The degree of prefabrication affects the requirements of manpower. The more works to be done on site (that is the less prefabrication), the more workers are required. The structures that require the least workers are steel and precast structures. The use of partial precast components could also reduce the number of workers required on-site. Cast-in-place post-tensioned structures require approximately the same number of workers as the cast-in-place reinforced concrete structures, but they require shorter time to complete. On the other hand, the technologies to construct the cast-in-place structures also affect the buildability. For instance, table formwork and steel scaffolding take less time to install than normal formwork and wooden scaffolding. It is the responsibility of the contractors to select the methods of construction. Nowadays, the contractors would like to reduce the number of workers on site since it is difficult to find and to manage these laborers.

Another criterion that determines the number of workers required is project schedule. The project with tighter schedule requires more workers and/or more shifts of work. Nevertheless, the safety on site should always be the top priority. The contractors can consider changing the construction method or proposing alternative designs instead of increasing the number of labors to shorten the construction duration.

5.6.10 Requirement of Labor skill

The designs that require less number of labors would require higher level of skill from each worker. The main skill requirements of the building construction can be divided into structural, MEP, and architectural/finishing. The skill requirements for structural works can be assessed by the types of structures. The skill requirements of structure in descendent order are composite structure, steel structure, precast structure, cast-in-place post-tensioned structure, and cast-in-place reinforced concrete structure. The assessment of skill for architectural works can be based on the types of walls. Brick walls are the most commonly used type of walls for both partition and exterior, and thus require the lowest skill. Dry gypsum walls, which are mainly used for partitions, are easy to install and require less labors than the conventional brick walls. The gypsum walls are getting more popular for office buildings and shopping malls, but they are still less popular than the brick walls, and therefore requires higher level of skill.

Curtain walls or glass walls are mainly used in commercial buildings, especially the high-rise buildings. The materials of curtain walls are imported, mostly from China, and there are not many technicians capable to install them. The contractors without adequate skills need to subcontract the works to specialized companies. For MEP works, many MEP suppliers also provide the installation services given where the contractor prepares the structure and purchase the products from these suppliers. The contractors who have less skill would outsource the MEP works (e.g. installation of fire alarm, sprinkling system, air conditioning, lift) to specialized companies. In some uncommon cases, the contractors need to import the machines from abroad and install these machines themselves. This would significantly increases the difficulty of MEP works. For example, in the multimedia center project, the contractor needed to purchase the newspaper press from abroad and install the machine using the installation manual. This would significantly increases the difficulty of MEP works.

5.6.11 Design to Suit Site Conditions

There are three main criteria to evaluate if the designs are suit the site conditions. They are site occupation, soil investigation, and compliance with local regulations.

The free space on site determines the designs of site layouts and the installation process of temporary facilities, such as site office, guard house, warehouse, stock yard, workshop, temporary toilet, and workers' accommodation. The rule of thumb given by the respondents is that the building should occupy less than 50% of the total site area. The actual conditions could be varied according to the size of the work and the land available. For sites with less free space, some temporary facilities might need to be relocated several times from the beginning till the end of the project. For example, the site office might be first located outside the site (in case there is no free land) or outside the building layout. Once the scaffolding of the ground floor or basement is removed, the site office is relocated into the building. The site office is moved out of the building again (possibly to the garden area) at the end of the project so the architectural works could be completed. In contrast, for site with sufficient free space, all the temporary facilities could stay at the same place throughout the project period which could save both time and costs.

Soil investigation is essential for the designs of the master plan and the structure of the building. A good soil investigation report should not only indicate the detailed locations and the properties of soil stratum, but should also include the existing underground structures, the piping and wiring of water and electricity lines. Unexpected encounters of poorer soil conditions and existing structures due to inaccurate soil investigation can delay the construction schedule and will be a source of conflicts. Moreover, for poor soil conditions, the designers should try to minimize the underground works, for instance by reducing the number of storeys of the basement.

The last criterion is to design the building in compliance with local regulations. The architects need to check the compliance of their designs with the local regulations, such as the maximum height of the building, the distance from the centerline of public road, and the permitted building area of the land. The designers and the contractors should give advice to the owner to correct any noncompliance of the applicable building regulations.

5.6.12 Design to Support Transportation of Materials and Labors

The main points to be checked are the efficient travel of machines, materials and workers in the site, the adjacency of the surrounding buildings, the installation of tower crane, and the proximity to main roads.

There should be at least two meters free space between the neighboring buildings and the building under construction so that the scaffolding and the safety net could be installed. To facilitate transportation, the constructing building should have more than four meters distance from the surrounding buildings so that the trucks could travel around. These are also the working spaces for the pile boring machines or the driving machines to install the perimeter and corner piles.

Tower crane is the decisive criterion for the transportation of materials within the site. It should have full coverage over the building, the stockyard, and the workshops to facilitate the transportation of materials and machines. For large projects, more than one tower crane might be needed to ensure full coverage and increase the speed of transportation. For projects with small building area or lower height (less than five storeys), a mobile crane or other smaller hoisting devices might be more economical. However, these devices might not be able to lift the formworks.

Proximity to the main roads affects the transportation of materials from outside into the construction site. There should be at least one large enough access road to the site so that the trucks could travel into. In some cases that the truck could not get into the site, all materials and the equipment are required to be shipped by the workers using the carts. This is a very laborious and time consuming work and should be avoided if possible. In contrast, if one or more sides of the building are next to the main roads, all the materials could be hoisted directly from the trucks parking at the roadside by the tower crane into the site. Therefore, the proximity or the access to the main roads is a very important factor to facilitate the transportation of materials and machines from the suppliers to the site.

5.7 Conclusion

This chapter describes about the development process of buildability assessment model. The model is developed based on the AHP by aggregating the judgments of 28 respondents. The goal of the model is the buildability of design documents. The second level is the criteria of buildability which are design documents, resources, and site layout. The third level is the factors to evaluate the buildability which include standardization of designs, simplicity, coordination between design documents, completion of design documents, clarity of specifications, underground construction, availability of materials, availability of machines and equipment, requirement of manpower, requirement of labor skill, design to suit site conditions, and design to support transportation. The lowest level is the Liberatore rating scale. The users are required to evaluate the design documents by using the Liberatore rating scale to evaluate each buildability factor. The subcriteria of each buildability factor and the current practices to achieve average buildability are described in this chapter so that the users have a common basis of assessment.

CHAPTER VI
VALIDATION OF BUILDABILITY ASSESSMENT MODEL

Upon the development of the buildability assessment model, this model was validated by scoring the buildability of 11 building projects. The results from the model and the perceptions of the respondents were compared and discussed.

6.1 Description of Data Collection

The data treated in this chapter corresponds to the answers in Part II of the validation survey. Before the respondents used the five-point scale (very good, good, average, fair, and poor) to evaluate each buildability factor in order to obtain the buildability score of the designs, they were asked to provide the details of the current practice of the designs (Part I of validation survey) to achieve these buildability factors and the information of the projects they were going to evaluate. Finally, they were asked to provide the general impression about the designs of the project under consideration. Eleven projects were evaluated, 5 of them were cross-checked by more than one evaluator to verify the bias of the assessment. The data were collected in two parts, the first part of 10 samples were collected from June 15 to 29, 2014 and the second part of additional 10 samples were collected from September 7 to 14, 2014.

6.2 Scoring Buildability of Building Projects

The respondents were required to evaluate each buildability factor by using the Liberatore Five-Point rating. The details of why the rating was given to each factor were also recorded. Table 6.1 shows the information about the building projects evaluated by the respondents.

There were 11 private building projects used in the validation process of the buildability assessment model. All projects have basements less than 3 storeys and among them 8 projects have more than 11 storeys and could be classified as high-rise buildings. All of the building projects are located in Phnom Penh city.

- Project 1. A private multipurpose building that has a rectangular shape with cast-in-situ post-tensioned drop panel slabs, reinforced concrete walls and columns, plastered brick partitions, glass curtain facades without balcony, and

2 basement floors. The first 5 storeys are designed as shopping center and the storeys above are 390 condominium units.

- Project 2. A private condominium building that has cast-in-situ post-tensioned slabs, reinforced concrete walls and columns, with 12 storeys supper structure and 2 basement floors. The layout of the ground floor is unique while the layouts from the 4^{th} to 9^{th} floor are the same. The layout changes again for the 10^{th} to 12^{th} floor.
- Project 3. A private multipurpose building in the same project as Case 1. The number and the function of the storeys are the same except that this building has a curved shape and an indoor atrium patio supported by major inclined columns cutting through the first 5 floors.
- Project 4. A private hotel project that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades, and swimming pool on top floor. The T-shaped building has unequal wings and non-repetitive gridlines. The building layout occupancy of this building is 100%. A semi-storey basement was chosen to facilitate the construction.
- Project 5. A private villa project that has cast-in-situ reinforced concrete frames and slabs (5 meters high for each storey), plastered brick partitions and facades, tiled hipped roof. Due to the time constraint, the project manager took special attention to improve the buildability by checking the coordination and the completeness of the design documents before construction. The project was able to be finished in six months.
- Project 6. A private hotel project that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades. The basement is 3.5 meters deep and was constructed next to a river with poor soil conditions and water ingression. The layouts and the heights of the ground floor and 13^{th} floor are different from the other floors of the superstructure.
- Project 7. A multipurpose private building that has cast-in-situ post-tensioned slabs, cast-in-situ concrete frames, plastered brick partitions, and glass curtain facades. The building has 3 basement storeys. The first 3 storeys of the superstructure are designed as newspaper office, and the other 9 storeys are

designed as offices for rent. The project is very close to the neighbors in which the project requires the use of bored piles as soil retaining structure.

- Project 8. A private apartment project that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades. The building has 8 storeys without basement. The project is located in a small alley that the trucks could not access, all the materials are transported by workers using carts. The tower crane and others heavy machines were not able to be installed. The pipe of concrete pump was routed through the neighboring buildings to access the project. There was no free space between the building under construction and the neighboring buildings, thus it was very difficult to make the exterior architectural works.
- Project 9. A private residential building that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades. The building has 24 floors, B1 and F2 – F4 serve as a car park, while F5 – F24 are apartment or condominium. This building is a part of a four buildings project located in suburb area near the riverside. The site area is large, the soil conditions are good, and there is no water ingression from the river.
- Project 10. A private residential building that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades. The building has 34 floors, B1 and B2 serve as a car park, F2 – F34 are apartment or condominium. The L-shaped building is located in the downtown area next to the river. The site is small and there is water ingression from the river.
- Project 11. A private hotel and condominium building that has cast-in-situ reinforced concrete frames and slabs, plastered brick partitions and facades. The building is to be certified as a five-star hotel and has 22 floors above ground level and one storey for the basement. The building is divided into three parts, where two parts serve as hotel and the other as condominium. The construction areas for each floor are 2000 sq. m. which are divided into 50 – 70 rooms. The site areas are large, located alone at the riverside. The building also has 2 helicopter landing platforms on the roof.

Table 6.17 Information of Project to Be Validated

No.	Project Name	Type	Project Details
1	Olympia City Project Building S2	Multipurpose	2 basement floors, 5 storeys as shopping center, another 21 storeys as condominium
2	Condominium Project	Condominium	2 basement floors, 12 storeys as condominium
3	Olympia City Project Building S3	Multipurpose	2 basement floors, 5 storeys as shopping center with atrium patio, another 21 storeys as condominium
4	Sun and Moon Hotel	Hotel	1 basement floor, 9 storeys as hotel, swimming pool on top floor
5	Villa Project	Villa	3 storeys
6	Toyoko Inn Hotel	Hotel	1 basement floor, 21 storeys as hotel
7	Koh Santepheap Media Center	Office	3 basement floors, 3 storeys as in-house office, 9 storeys as office for rent
8	Apartment Project	Apartment	8 storey apartment
9	Bali Resort (Chaktomuk)	Residence	B1, F2-F4 as parking, F5 – F24 as apartment and condominium
10	Bali Resort (Koh Pich)	Residence	B1 and B2 as parking, F2 – F34 as apartment and condominium
11	Sokha Hotel	Hotel and Condominium	1 basement floor, 22 storeys, 2/3 of building as hotel, 1/3 as condominium

The Liberatore ratings given by the respondents to each factor were translated to AHP weights and then multiplied by the global weights of the corresponding buildability factors. The buildability score of a project is the sum of the 12 products between the weight of the rating scale and the global weight of each buildable factor

(See Table 6.2). The final numerical buildability score is then interpreted into different grades to facilitate the understanding of the users. The cutting points for each grade are the same as the Liberatore rating scale that are used to evaluate each buildability factor, which is greater 0.034 is poor (P), greater than 0.063 is fair (F), greater than 0.129 is average (A), greater than 0.261 is good (G), and equal to 0.512 is outstanding (O). The interpreted results are then compared with the overall impressions of the respondents of the projects. Table 6.3 illustrates the buildability score, the interpretation of the score and the impressions of the respondents. The full results of scorings of the 11 projects are attached in Appendix C.

Table 6.18 Application of the AHP Model on Building Construction Project 1

Buildability Factor	Global weights	Project 1 Rating	Score	× GW
Standardization of designs	0.045	G	0.261	0.012
Simplicity	0.030	G	0.261	0.008
Coordination	0.053	A	0.129	0.007
Completion of design documents	0.068	F	0.063	0.004
Clarity of specifications	0.045	G	0.261	0.012
Underground construction	0.032	G	0.261	0.008
Availability of materials	0.087	G	0.261	0.023
Availability of machines and equip	0.081	G	0.261	0.021
Requirement of manpower	0.084	F	0.063	0.005
Requirement of labor skill	0.125	F	0.063	0.008
Design to suit site conditions	0.162	F	0.063	0.010
Design to support transportation	0.186	G	0.261	0.049
Total Scores	1.000			0.167
Percentage of Best Design				32.5%
Expectation of Respondent				Average
Interpretation of Score *				Average

* Score: = 0.513 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

A total of 20 samples were collected to test the validity of the model. The respondents were asked to evaluate the buildability of the current project or the project that they have just completed by using the model. Among the 11 projects, 1 project was crosschecked by 4 respondents, 2 projects were crosschecked by 3 respondents, and 2 projects were crosschecked by 2 respondents, the remaining 6 projects were not crosschecked.

Frist the discrepancy between the output of the model and the expectations of the respondents was discussed. Then the bias among different evaluators of the same project is discussed.

Table 6.19 Summary of AHP Model Scoring Results

No.	Buildability Score	Interpretation	Expectation
Project 01	0.167	Average	Average
	0.146	Average	Average
	0.211	Average	Average
Project 02	0.235	Average	Average to Good
	0.232	Average	Average to Good
Project 03	0.354	Good	Good
Project 04	0.328	Good	Good
	0.172	Average	Average
	0.130	Average	Average
Project 05	0.365	Good	Good
Project 06	0.424	Good	Outstanding
	0.201	Average	Good
	0.189	Average	Average
	0.210	Average	Good
Project 07	0.288	Good	Good
Project 08	0.249	Average	Average
Project 09	0.227	Average	Good
Project 10	0.206	Average	Good
Project 11	0.296	Good	Good
	0.312	Good	Good

Among the 20 samples, the scorings of the models of 5 samples were one grade lower than the expectations of the evaluators. The scorings of the models of the other 15 samples were the same with the expectations of the evaluators. This signifies that the model could reflect the buildability expectations of the respondents with some degrees of conservative estimation. This might be because the evaluators tend to give higher weights to the buildability factors that have good buildability than those have poor buildability. It is known that the evaluators are prone to be over influenced by positive instances and under influenced by negative instances (Phillips, 1987).

For the 5 samples that have been crosschecked, the evaluators of 3 samples gave the same grades of buildability while the evaluators of the other 2 samples had some disagreement. There was one evaluator in the group rated higher buildability than the others, but the difference was not significant. The evaluator who has more experiences tends to give a higher score than the other. In conclusion, the model has low bias due to different evaluators.

The differences between the results of the model and the expectations of the respondents might be owing to the scales of the Liberatore AHP model. Thus, it assumes that the function of the buildability and the buildability score are of second degree exponential polynomial relationship, i.e. the weight of the higher level is constantly two times of the immediate lower level. However, the perceptions of the respondents about the relationship between buildability and buildability score might be ordinal, i.e. the weight of the higher level is only one point higher than the immediate lower level.

The bias of the evaluators of the model could be eliminated through face-to-face group discussion among them to reach a consensus about the score of each buildability factor before calculating the buildability score of the whole designs.

6.3 Discussion

The proposed model is a useful tool to evaluate the buildability of building designs as a whole as well as to evaluate the buildability of specific aspects of the designs. The overall buildability score gives a general evaluation of the building designs. If the overall score is below average, then the designers can review the score of each buildability factor and focus on the factors that have low scores. The designers should start the improvements with the factors that have high weights.

For the buildability factors that have the scores less than average, the designers can review the current and best practices of designs of corresponding factors and make relevant improvements. Alternatively, the designers can also concentrate the improvements on the buildability factors that have high weights.

There are three kinds of validity proposed by Schellenberger (1974): (1) technical validity, (2) operational validity, and (3) dynamic validity. The validity of the buildability assessment model developed was discussed with respect to the criteria suggested by Schellenberger for each kind of validity.

6.3.1 Technical Validity

Technical validity refers to a set of criteria against which any application of analysis could be compared. There are four components of technical validity: (1) model validity, (2) data validity, (3) logical validity, and (4) predictive validity.

Model validity refers to the degree of correspondence between the model and the real world. That is whether the buildability score obtained from the model reflects the ease of construction from the perspectives of the constructors. Through the interviews, all the respondents agreed that the output of the buildability assessment model represented the degree of buildability of the design documents. The validity of mathematical assumptions about the sum of the products between the Liberatore rating scale and the weight of AHP were discussed in the studies of Liberatore (Liberatore, 1987, Liberatore et al., 1992).

Data validity is divided into the validity of raw data and the validity of structured data. The validity of raw data concerns with the accuracy, the impartiality and the representativeness of the data. The accuracy and the impartiality of measure of AHP were discussed by Saaty (Saaty, 1980, Saaty, 1986, Saaty, 1990, Saaty, 2008). The representativeness of the data was assured by the convenience sampling due to the difficulty of getting a list of all construction professionals. From the results of sampling, we can see that the respondents were from different sizes of companies ranging from small to major contractors with various construction experiences. The validity of using the geometric mean to aggregate the pairwise comparisons of the respondents in AHP in group decision making was discussed by Ishizaka and Labib (2011).

Logical validity refers to the logical progression from the model development to the solution. The first step to develop this model is to identify important factors relevant to the buildability. This process is achieved by using one-sample *t*-test to evaluate the ratings of the respondents. The second step is to determine the weight of the buildability factors through the AHP. The last step is to use the Liberatore rating scale to evaluate each buildability factor of the model, instead of making the pairwise comparisons between the alternatives, to get the final buildability score. The logical validity of the development of each step is supported by sound research and scientific methods developed by previous researchers as discussed in Chapter 3. The final buildability score is then translated back to the rating scale of Liberatore to make the final output more understandable to the users.

Predictive validity concerns about the errors between the actual outcomes and the predicted outcomes of the model. The predictive validity of this model was tested by scoring the buildability of 11 building projects. The results were that among the eleven projects, the answers of the model and the respondents' impressions were the same for 15 samples and the other 5 samples were one grade lower than the respondents' impressions. The results of the model could be perceived as more objective, comprehensive, and accurate than the general impressions of the respondents on buildability. The respondents tended to focus on a few aspects of the designs rather than comparing all the 12 buildability factors systematically when giving the general impressions of the buildability of designs. Since buildability is a concept, the predictive validity was only tested by comparing the respondents' impressions with the buildability scores.

6.3.2 Operational Validity

Operational validity deals with the importance of discrepancy of the technical validity. In this study, there was consistently one grade lower rating given by the buildability assessment model compared with the general impression of the respondents. The difference might be due to the personal bias on more favorable factors and the lack of comprehensive considerations of all buildability factors by the respondents during the evaluation. Therefore, it is not necessary to modify the rating scale of the model.

This model has only two extremes, the minimum when all the factors are rated poor and the maximum when all the factors are rated outstanding. The sum of ratio values from all the buildability factors results in a ratio value. There is no optimum result from the model.

6.3.3 Dynamic Validity

Beside technical validity and operational validity, dynamic validity focuses on the validity of the model throughout its life cycle. As the construction industry develops, new construction techniques, materials and equipment will be introduced to the markets. Consequently, the contents of some factors, subcriteria, and current practices would need to be updated to adapt to the environment. The model developed in this study provides a conceptual framework for the user to add, remove, or change the factors and their weights as needed. However, it should be aware that this model is the aggregation of the opinions of many construction practitioners in different phases of the model development, the modifications of any individual item should be made with attentions.

6.4 Conclusion

This chapter discusses about the validation process of the model. The buildability scores of 11 building projects were obtained from using the proposed model. It can conclude that this model presents an acceptable technical validity. Based on the impressions of the respondents, the buildability score produced by the model corresponded well with the ease of actual building construction.

CHAPTER VII
RESEARCH CONCLUSIONS

7.1 Research Findings

Construction problems caused by the designs are common issues in the Cambodian construction industry. This research aims to incorporate the construction experience of the contractors in the design processes so that the potential issues could be eliminated before the construction. All the findings of this research were derived from the perspective of the contractors.

The first output of this research is a list of important factors that affect the buildability of designs rated by 35 respondents using the 5-point Likert scale. The top five factors ranked by their means are (1) standardization of designs (mean = 4.51); (2) completion of design documents (mean = 4.43); (3) clarity of specifications (mean = 4.43); (4) requirement of labor skill (mean = 4.29); (5) design to suit site conditions (mean = 4.29); (6) simplicity (mean = 4.20); (7) availability of materials (mean = 4.11); (8) design to support transportation of labors and materials (mean = 4.11); (9) coordination between design documents (mean = 4.09); (10) requirement of manpower (mean = 4.06); (11) availability of machines and equipment (mean = 3.97) and (12) underground construction (mean = 3.91).

The second output of the research is a list of the AHP weights of the buildability criteria and the buildability factors based on the judgments of 28 respondents. The weights of the buildability criteria are (1) resources (0.377); (2) site layout (0.348); and (3) design documents (0.275). The global weight of the buildability factors are (1) design to support transportation (0.186); (2) design to suit site conditions (0.162); (3) requirement of labor skill (0.125); (4) availability of materials (0.087); (5) requirement of manpower (0.084); (6) availability of machines and equipment (0.081); (7) completion of design documents; (8) coordination between design documents (0.053); (9) standardization of designs (0.045); (10) clarity of specifications (0.045); (11) underground construction (0.032); and (12) simplicity (0.030).

The third output of this research is the model to evaluate the buildability of the design documents. The model is based on the AHP structure, the top of the structure is the goal of the model which is the buildability score of a design, the second level of the structure is the buildability criteria, the third level of the structure is the buildability factors, and the level bottom is the Liberatore 5-point rating scale. When assessing the buildability of a design, the users are required to use the Liberatore rating score to evaluate every buildability factor. The buildability score is calculated by summing the products between the global weights of the buildability factors and the weights of the corresponding Liberatore rating scale.

The final outputs of the research are the subcriteria of the buildability factors and the current practices of the designs related to these subcriteria which can help users to evaluate the buildability of the designs more objectively. The subcriteria allow the users to assess the buildability of a design in more details while the current practices are the references for the users to evaluate the designs. The designs that are complied with the common current practices can be evaluated as the designs that have average buildability.

7.2 Research Contributions

This model will be a useful tool for the designers to check and benchmark the buildability of their designs at detailed design stage, before the submission to the owner for bidding. The buildability concepts and the factors in this research are also applicable at earlier design phases, such as the scheme design phase and the development of design phase. The buildability evaluation at earlier design phases will be more beneficial for the improvement of buildability. Earlier improvement of designs will have greater positive influences on construction. It is easier to make changes in the early design phases to improve the buildability than in the latter project phases. By using the model, the designers can focus on the main factors that have low buildability and take necessary strategies to improve their designs.

This research provides the perceptions of the Cambodian contractors about the buildability and gives a view of how the buildability concepts vary from countries to countries. The detailed knowledge of the subcriteria to evaluate the buildability factors and the current practices related to these subcriteria are useful for the designers to improve the buildability in the Cambodian construction industry context which is less developed and more accustomed to the traditional cast-in-situ RC structures.

7.3 Research Limitations

This model was developed under certain limitations. First, the samples used to develop this model were collected only from the local and the joint-ventures contractors in Phnom Penh city. The opinions of the designers, the owners, and the consultants concerning this matter are still to be studied. Moreover, all the projects used in the validation process were private mid- and high-rise building projects. The applicability of this model on low-rise buildings and skyscrapers is to be investigated.

The consistency of this model was tested by crosschecking the buildability scores of different respondents on the same project. Among the five samples that have crosschecked, the evaluators of three samples gave the same grades of buildability. The evaluators of the other two samples provided different outputs, one of the evaluators in the two samples gave one grade lower buildability ratings.

The discussion of the validity of this model was based on the correspondence between the buildability score and the opinions of the respondents, but not between the buildability score and the actual economic/quantitative benefits. In addition, since the size of samples was small and most of the respondents of this research had experiences only in cast-in-situ reinforced concrete structures, the actual buildability of the other types of structures were unknown.

7.4 Further Studies

The suggestions for the studies are:

(a) The studies of buildability issues from the perspectives of designers, owners, and consultants are still to be conducted.

(b) An update of the buildability knowledge to suit the development of the construction industry might be necessary for the studies in the future.

(c) The researchers could include maintenance, operation, and demolition in the buildability considerations to extend the concepts to the whole building lifecycle.

REFERENCES

1982. Integrating construction resources and technology into engineering. *Construction Industry Cost Effectiveness Project Report, Report B-1A.* New York: Business Roundtable

(CII), C. I. I. 1986. Constructability: a primer. Austin, Texas: Construction Industry Institute, University of Texas.

(CII), C. I. I. 1987. Constructability Concepts File. *In:* INSTITUTE, C. I. (ed.). Austin, Texas.

(CII), C. I. I. 1993. Constructability Implementation Guide. *In:* INSTITUTE, C. I. (ed.) *Special publication 34-1.* Austin, Texas.

(CII), C. I. I. 1997. Constructability Guidelines. Austin, Texas, USA: Construction Industry Institute

(EDC), E. D. C. 1967. Action on the Banwell Report. *In:* HMSO (ed.). London.

(NEDO), N. E. D. O. 1975. The Wood Report: The Public Client and The Construction Industry. *In:* HMSO (ed.). London.

AASHTO/NSBA 2003. Guideline for Design for Constructability. AASHTO/NSBA Steel Bridge Collaboration.

AIBINU, A. A. & ODEYINKA, H. A. 2006. Construction Delays and Their Causative Factors in Nigeria. *Journal of Construction Engineering and Management,* 132**,** 667-677.

AMARATUNGA, D., BALDRY, D., SARSHAR, M. & NEWTON, R. 2002. Quantitative and qualitative research in the built environment: application of “mixed” research approach. *World Study,* 51**,** 17-31.

ANDERSON, S. D., FISHER, D. J. & RAHMAN, S. P. 1999. Constructability Issues for Highway Projects. *Journal of Management in Engineering,* 15**,** 60-68.

ANDERSON, S. D., FISHER, D. J. & RAHMAN, S. P. 2000. Integrating constructability into project development: a process approach. *Journal of Construction Engineering and Management,* 126**,** 81-88.

ARDERY, E. R. 1991. Constructability and constructability programs: White paper. *Journal of Construction Engineering and Management,* 117**,** 67-89.

ARDITI, D., ELHASSAN, A. & TOKLU, Y. C. 2002. Constructability Analysis in the Design Firm. *Journal of Construction Engineering and Management,* 128**,** 117-126.

AUSTRALIA, C. I. I. C. 1993. Constructability Principles File. *In:* AUSTRALIA, C. I. I. (ed.). Adelaide, Australia: University of South Australia.

BANWELL, H. 1964. The Placing and Management of Contracts for Building and Civil Engineering Work: Report of the Committee. *In:* HMSO (ed.). London.

BARZILAI, J. 1997. Deriving Weights from Pairwise Comparison Matrices. *Journal of Operational Research Society,* 48**,** 1226-1232.

BARZILAI, J. Understanding Hierarchical Process. Proceeding of the 19th Annual Meeting of the American Society for Engineering Management, 1998. 1-6.

BARZILAI, J. Note on the Analytic Hierarchy Process. Proceeding of the NSF Design and Manufacturing Research Conference, 2001. 1-6.

BCA 2000. *In:* AUTHORITY, B. A. C. (ed.). Singapore: Code of Practice on Buildable Design.

BCA 2013. Code of Practice on Buildability. Singapore: Building and Construction Authority.

BOOS, D. D. & HUGHES-OLIVER, J. M. 2000. How Large Does n Have to be for Z and t Interval? . *The American Statistician,* 54**,** 121-128.

CHOO, E. U., SCHONER, B. & WEDLEY, W. C. 1999. Interpretation of Criteria Weights in Multicriteria Decision Making. *Computer & Industrial Engineering,* 37**,** 527-541.

CIDB 1989. Cost Competitiveness of the Construction Industry of Singapore. *CIDB Task Force Report.* Singapore: Construction Industry Development Board.

CIDB 1992. Raising Singapore's Construction Productivity. *CIDB Task Force Report.* Singapore: Construction Industry Development Board.

CIDB 1993. Buildable Design Appraisal System. Singapore: Construction Industry Development Board.

CIRC 2001. Construct for Excellence. *Report of the Construction Industry Review Committee.* Hong Kong: CIRC.

CIRIA 1983. Buildability: An Assessment. London: Construction Industry Research and Information Association.

CORTINA, J. M. 1993. What Is Coefficient Alpha? An Examination of Theory and Applications. *Journal of Applied Psychology,* 78**,** 98-104.

CRONBACH, L. J. 1951. Coefficient Alpha and the Internal Structure of Tests. *Psychometrika,* 16**,** 297-334.

DYER, J. S. 1990. Remarks on the Analytic Hierarchy Process. *Management Science,* 36**,** 249-258.

EASTERBY-SMITH, M. 1991. *Management Research: An Introduction,* London, SAGE Publications.

EGAN, J. 1998. Rethinking Construction: the report of the Construction Task Force to the Deputy Prime Minister, John Prescott, on the scope for improving the quality and efficiency of UK construction. London: Dept. of the Environment, Transport and the Regions.

ELDIN, N. N. 1999. Impact of employee, management, and process issue on constructability implementation. *Construction Management and Economics,* 17**,** 711-720.

EMMERSON, H. 1962. Survey of Problem before the Construction Industry: a report prepared for the Ministry of Works. *In:* HMSO (ed.). London.

EMPORIS. *Datas Standards (ESN 18727)* [Online]. Available: http://www.emporis.com/building/standards/high-rise-building [Accessed 30 August 2014].

EMPORIS. *Datas Standards (ESN 49213)* [Online]. Available: http://www.emporis.com/building/standards/low-rise-building [Accessed 30 August 2014].

ERBERIK, M. A. 2008. Fragility-based assessment of typical mid-rise and low-rise RC buildings in Turkey. *Engineering Structures,* 30**,** 1360-1374.

FELLOWS, R. & LIU, A. 2008. *Research Methods for Construction* Oxford, Blackwell Science Limited.

FISCHER, M. & TATUM, C. B. 1997. Characteristics of Design-Relevant Constructability Knowledge. *Journal of Construction Engineering and Management,* 123**,** 253-260.

FOLKESTAD, B. 2008. Analysing Interview Data: Possibilities and Challenges. *Eurosphere Online Working Paper Series, Working Paper No. 13*.

FORD, D. N., ANDERSON, S. D., DAMRON, A. J., CASAS, R. D. L., GOKMEN, N. & KUENNEN, S. T. 2004. Managing Constructability Reviews to Reduce Highway Project *Journal of Construction Engineering and Management,* 130**,** 33-42.

FRANCIS, V. E., CHEN, S. E., MEHRTENS, V. M., SIDWELL, A. C. & MCGEORGE, W. D. 1999. Constructability Strategy for Improved Project Performance. *Architectural Science Review,* 42**,** 133-138.

FRANCIS, V. E., SIDWELL, A. C. & CHEN, S. E. 1996. Constructability Manual. *In:* CONSTRUCTION INDUSTRY INSTITUTE, A. (ed.). Adelaide: University of South Australia.

GIBSON, G. E., MCGINNIS, C. I. & FLANIGAN, W. S. 1996. Constructability in public sector. *Journal of Construction Engineering and Management,* 122**,** 274-280.

GLAVINICH, T. E. 1995. Improving Constructability during Design Phase. *Journal of Architectural Engineering,* 1**,** 73-76.

GRIFFITH, A. 1984a. Buildability: The effect of design and management on Construction: a case study. *In:* EDINBURGH: HERIOT-WATT UNIVERSITY, D. O. B. (ed.).

GRIFFITH, A. 1984b. *A critical investigation of factors influencing buildability and productivity.* Doctoral dissertation, University of Heriot-Watt.

GRIFFITH, A. & SIDWELL, A. C. 1997. Development of Constructability Concepts, Principles and Practices. *Engineering, Construction and Architectural Management,* 4**,** 295-310.

GUGEL, J. G. & RUSSELL, J. S. 1994. Model for constructability approach selectio. *Journal of Construction Engineering and Management,* 120**,** 509-521.

HARTMANN, T. & FISCHER, M. 2007. Supporting the constructability review with 3D/4D models. *Building Research and Information,* 35**,** 70-80.

HASSAN, Z. & ABDUL KARIM, M. S. 2008. Buildability Analysis in an Integrated Computer Application. *International Conference on Construction and Building Technology.*

HECKER, S. & GAMBATESE, J. A. 2010. Safety in Design: A Proactive Approach to Construction Worker Safety and Health. *Applied Occupational and Environmental Hygiene,* 118**,** 339-342.

HIJAZI, W., ALKASS, S. & ZAYED, T. 2009. Constructability Assessment Using BIM/4D CAD Simulation Model. *AACE International Transactions.* Morgantown WV: AACE.

HON, S. L., GAIRNS, D. A. & WILSON, O. D. 1989. Buildability: A Review of Research and Practice. Australia: Australian Institute of Building (AIB).

HSIEH, H. F. & SHANNON, S. E. 2005. Three Approaches to Qualitative Content Analysis. *Qualitative Health Research,* 15**,** 1277-1288.

HUGO, F., O'CONNOR, J. T. & WARD, W. V. 1990. Highway Construction Guide. *In:* TEXAS, U. O. (ed.). Austin.

HWANG, B., ZHAO, X. & GOH, K. J. 2014. Investigating The Client-related Rework in Building Projects: The Case of Singapore. *International Journal of Project Management,* 32**,** 698-708.

IRELAND, V. 1985. The role of managerial actions in the cost, time and quality performance of high-rise commercial building projects. *Construction Management and Economics,* 3**,** 59-87.

ISHIZAKA, A. & LABIB, A. 2011. Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications,* 28**,** 14336-14345.

JARKAS, A. M. 2010a. Buildability Factors Influencing Micro-Level Formwork Labour Productivity of Slab Panels in Building Floors. *Architectural Engineering and Design Management,* 6**,** 161-174.

JARKAS, A. M. 2010b. The effects of Buildability Factors on Rebar Fixing Labour Productivity of Beamless Slabs. *Australasian Journal of Construction Economics and Building,* 10**,** 16-35.

JARKAS, A. M. 2010c. The impacts of buildability factors on formwork labour productivity of columns. *Journal of Civil Engineering and Management,* 16**,** 471-483.

JARKAS, A. M. 2010d. The influence of buildability factors on rebar fixing labour productivity of beams. *Construction Management and Economics,* 28**,** 527-543.

JARKAS, A. M. 2012. Analysis and Measurement of Buildability Factors Influencing Rebar Installation Labor Productivity of In Situ Reinforced Concrete Walls. *Journal of Architectural Engineering,* 18**,** 52-60.

JERGEAS, G. & PUT, J. V. D. 2001. Benefits of constructability on construction projects. *Journal of Construction Engineering and Management,* 127**,** 281-290.

KOTHARI, C. R. 2004. *Research Methodology – Methods & Techniques,* New Delhi, New Age International (P) Limited.

LAM, P. T. I. 2002. Buildability assessment: the Singapore approach. *Journal of Building and Construction Management,* 7**,** 21-27.

LAM, P. T. I., WONG, F. W. H. & CHAN, A. P. C. 2005. Contributions of designers to improving buildability and constructability. *Design Studies,* 27.

LAM, P. T. I., WONG, F. W. H., CHAN, A. P. C., SHEA, W. C. Y. & LAU, J. W. S. 2012. A Scheme Design Buildability Assessment Model for Building Projects. *Construction Innovation,* 12**,** 216-238.

LIBERATORE, M. J. 1987. An Extension of the Analytic Hierarchy Process for Industrial R&D Project Selection and Resource Allocation. *IEEE Transactions on Engineering Management,* 34**,** 12-18.

LIBERATORE, M. J. & NYDICK, R. L. 1997. Group decision making in higher education using the analytic hierarchy process. *Research in Higher Education,* 38**,** 593-614.

LIBERATORE, M. J. & NYDICK, R. L. 2008. The analytic hierarchy process in medical and health care decision making: A literature review. *European Journal of Operation Research,* 189**,** 194-207.

LIBERATORE, M. J., NYDICK, R. L. & SANCHEZ, P. M. 1992. The Evaluation of Research Papers (Or How to Get an Academic Committee to Agree on Something). *Interfaces,* 22**,** 92-100.

LOW, S. P. & ABEYEGOONASEKERA, B. 2001. Integrating buildability in ISO 9000 quality management systems: case study of a condominium project. *Building and Environment,* 36**,** 299-312.

MCGEORGE, W. D., CHEN, S. E. & OSTWALD, M. J. 1992. The Development of a Conceptual Model of Buildability Which Identifies User Satisfaction as a Major Objective. *ational Council for Building Research Studies and Documentation (CIB) Conference.* Rotterdam.

MYDIN, S. H., ZIN, R. M., MAJID, M. Z. A. & ZAHIDI, M. 2011. Buildability Problems in the Malaysian Building Construction. *IEEE Symposium on Business, Engineering and Industrial Applications (ISBEIA).*

NAOUM, S. G. 2007. *Dissertation Research and Writing for Construction Student,* Elsevier.

NIMA, M. A., ABDUL-KADIR, M. R. & JAAFAR, M. S. 2001a. Evaluation of the role of the contractor's personnel in enhancing the project constructability. *Structural Survey,* 19**,** 193-200.

NIMA, M. A., ABDUL-KADIR, M. R., JAAFAR, M. S. & ALGHULAMI, R. G. 2001b. Constructability Implementation: a survey in the Malaysian Construction Industry. *Construction Management and Economics,* 19**,** 819-829.

NKADO, R. N. 1995. truction time-influencing factors: the Contractor's Perspective. *Construction Management and Economics,* 13**,** 81-89.

NOURBAKHSH, M., MYDIN, S. H., ZIN, R. M., ZOLFAGHARIAN, S., IRIZARRY, J. & ZAHIDI, M. 2012. A Conceptual Model to Assess the Buildability of Building Structure at Design Stage in Malaysia. *Advanced Materials Research,* 446.

NUNNALLY, J. & BERNSTEIN, L. 1994. *Psychometric Theory,* New York, McGraw-Hill Higher, INC.

O'CONNOR, J. T. & DAVIS, V. S. 1988. Constructability improvement during field operations. *Journal of Construction Engineering and Management,* 114**,** 548-564.

OCST 1979. Building Control Act (B.E. 2522). Thailand: Office of the Council of State of Thailand (OCST).

PATTARANAWIC, W. & TONGTHONG, T. 2003. *Guidelines for Buildable Design for Factory Construction in Thailand.* Master thesis, Chulalongkorn University.

PATTON, M. 1990. *Qualitative evaluation and research methods,* London, Sage.

PEPPER, H. C. 1994. The benefits of constructability reviews during the design of environmental capital projects. *Cost Engineering,* 36**,** 19-21.

PHELLAS, C. N., BLOCH, A. & SEALE, C. 2011. Structured methods: interviews, questionnaires and observation. *Research Society and Culture.* London: SAGE Publication Ltd.

PHILLIPS, D. C. 1987. Validity in Qualitative Research Why the Worry about Warrant Will Not Wane. *Education and Urban Society,* 20**,** 9-24.

POCOCK, J. B., KUENNEN, S. T., GAMBATESE, J. & RAUSCHKOLB, J. 2006. Constructability State of Practice Report. *Journal of Construction Engineering and Management,* 132**,** 373-383.

POH, P. S. H. & CHEN, J. 1998. The Singapore buildable design appraisal system: a preliminary review of the relationship between buildability, site productivity and cost. *Construction Management and Economics,* 16**,** 681-692.

RUSSELL, J. S., GUGEL, J. G. & RADTKE, M. W. 1992. Benefits and Costs of Constructability: Four Case Studies. *In:* (CII), C. I. I. (ed.). Austin: University of Texas.

RUSSELL, J. S., GUGEL, J. G. & RADTKE, M. W. 1994a. Comparative analysis of three constructability approaches. *Journal of Construction Engineering and Management,* 120**,** 180-195.

RUSSELL, J. S., SWIGGUM, K. E., SHAPIRO, J. M. & ALAYDRUS, A. F. 1994b. Constructability related to TQM, value engineering and cost/benefits. *Journal of Performance of Constructed Facilities,* 8**,** 31-45.

SAATY, T. L. 1980. *The Analytic Hierarchy Process,* New York, the United States of America, McGraw-Hill, Inc.

SAATY, T. L. 1986. Axiomatic Foundation of the Analytic Hierarchy Process. *Management Science,* 32**,** 841-855.

SAATY, T. L. 1987. Rank Generation, Preservation, and Reversal in the Analytic Hierarchy Decision Process. *Decision Sciences*, 18**,** 157-177.

SAATY, T. L. 1990. How to make a decision: The Analytic Hierarchy Process. *European Journal of Operational Research,* 48.

SAATY, T. L. 2008. Decision making with the analytic hierarchy process. *Internatioanl Journal of Service Science,* 1**,** 83-98.

SAGHATFOROUSH, E., HASIM, A., JAAFAR, M. S. & ABDUL-KADIR, M. R. 2009. Constructability Implementation among Malaysian Building Contractors. *European Journal of Scientific Research,* 29**,** 518-532.

SAGHATFOROUSH, E., TRIGUNARSYAH, B., TOO, E. & HERAVITORBATI, A. Effectiveness of constructability concept in the provision of infrastructure assets. Proceeding of The First International Postgraduate Conference on Engineering, Design and Developing the Built Environment for Sustainable Wellbeing (EDBE2011), 7-10 February 2011 2011 Queensland University Technology, Brisbane. 175-180.

SAGHATFOROUSH, E., TRIGUNARSYAH, B., TOO, E. & HERAVITORBATI, A. Assessment of operability and maintainability success factors in provision of extended constructability principles. 9th International Congress on Civil Engineering, 8-10 May 2012 2012 Isfahan-Iran.

SCHELLENBERGER, R. E. 1974. Criteria for Assessing Model Validity for Managerial Purpose*. *Decision Sciences,* 5**,** 644-653.

SIEGEL, S. & CASTELLAN, N. J. 1988. *Nonparametric Statistics,* New York, McGraw-Hill.

SONG, L., MOHAMED, Y. & ABOURIZK, S. M. 2009. Early Contractor Involvement in Design and Its Impact on Construction Schedule Performance. *Journal of Management in Engineering*, 25**,** 12-20.

STAUB-FRENCH, S. Providing Cost and Constructability Feedback to Designers. Construction Research Congress 2003, 2003. 1-8.

SUBRAMANIY 2013. Cambodia: Country Report – Focus on Construction Sector. International Development Group.

TAM, M. C. Y. & RAO TUMMALA, V. M. 2001. An application of the AHP in vendor selection of a telecommunications system. *Omega*, 29**,** 171-182.

TAVAKOL, M., A., M. M. & DENNICK, R. 2008. Assessing the Skills of Surgical Residents Using Simulation. *Journal of Surgery Education,* 62**,** 77-83.

TAVAKOL, M. & DENNICK, R. 2011. Making Sense of Cronbach's alpha. *International Journal of Medical Education,* 2**,** 53-55.

TRIGUNARSYAH, B. 2004a. Constructability Practices among Construction Contractors in Indonesia. *Journal of Construction Engineering and Management*, 130**,** 656-669.

TRIGUNARSYAH, B. 2004b. Project owners' role in improving constructability of construction projects: an example for Indonesia. *Construction Management and Economics,* 22**,** 861-876.

TRIGUNARSYAH, B. 2004c. A review of current practice in constructability improvement: case studies on construction projects in Indonesia. *Construction Management and Economics,* 22**,** 567-580.

TRIGUNARSYAH, B. 2007. Project designer' role in improving constructability of Indonesian construction projects. *Construction Management and Economics,* 25**,** 207-215.

UGWU, O. O., ANUMBA, C. J. & THORPE, A. 2004. The development of cognitive models for constructability assessment in steel frame structures. *Advance in Engineering Software,* 35**,** 191-203.

UHLIK, F. T. & LORES, G. V. 1998. Assessment of Constructability Practices among General Contractors. *Journal of Architectural Engineering,* 4**,** 113-123.

VAIDYA, O. & KUMAR, S. 2004. lytic hierarchy process: An overview of applications. *European Journal of Operational Research,* 169**,** 1-29.

WEINSTEIN, M., GAMBATESE, J. & HECKER, S. 2005. Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Sate-in-Design Process. *Journal of Construction Engineering and Management,* 131**,** 1125-1134.

WINCH, G. & CARR, B. 2001. Benchmarking on-site productivity in France and the UK: a CALIBRE approach. *Construction Management and Economics,* 19**,** 557-590.

WONG, F. W. H. & LAM, P. T. I. 2008. Benchmarking of Buildability and Construction Performance in Singapore: Is there a case for Hong Kong? . *International Journal of Construction Management,* 8**,** 1-27.

WONG, W. H. 2007. *Developing and Implementing an Empirical System for Scoring Buildability of Designs in the Hong Kong Construction Industry.* Doctoral dissertation, The Hong Kong Polytechnic University.

YANG, Y. Q., WANG, S. Q., DULAIMI, M. & LOW, S. P. 2003. A fuzzy quality function deployment system for buildability design decision-making. *Automation in Construction,* 12**,** 381-393.

ZAHEDI, F. 1986. The Analytic Hierarchy Process – A Survey of the Method and its Applications. *Interfaces,* 16**,** 96-108.

ZIN, R. M., MAJID, M. Z. A., PUTRA, C. W. & MOHAMMED, A. H. 2004. Neural Network Model for Design Constructability Assessment. *Jurnal Teknologi,* 40**,** 27-40.

APPENDIX

APPENDIX A
Results of Importance Level of Factors Affecting Buildability

	Buildability factor of a building design																			
	Design							Resource				Flexibility				Site Layout and Safety				
ID	A1	A2	A3	A4	A5	A6	A7	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	D5
PM1	4	4	0	5	4	5	3	4	3	4	5	4	4	5	3	4	5	3	3	4
PM2	5	3	4	3	3	4	5	3	3	3	4	4	3	4	5	4	3	5	5	4
PM3	5	5	3	5	5	4	4	4	4	4	3	4	4	4	4	4	4	5	4	4
PM4	5	4	3	5	5	4	5	4	4	4	4	3	3	3	4	4	4	5	4	4
PM5	5	4	5	5	4	5	4	4	5	4	4	5	3	4	5	4	5	5	5	5
PM6	4	4	4	3	4	4	3	5	5	5	5	3	3	3	3	4	4	3	4	4
PM7	4	3	2	4	5	3	5	4	4	4	3	4	4	4	3	3	4	3	4	4
PM8	5	4	4	5	5	5	5	5	3	4	5	4	3	4	5	5	5	5	4	4
PM9	5	5	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
PM10	5	5	3	5	5	4	5	5	5	5	4	5	5	3	4	5	5	5	5	4
PM11	5	5	5	4	3	5	0	5	5	5	5	1	1	2	2	5	4	2	4	4
PM12	5	5	5	5	5	5	5	5	5	5	5	0	0	0	5	5	5	5	5	5
PM13	5	4	4	5	5	5	3	5	5	5	5	5	5	5	0	5	5	2	2	2
PM14	5	4	5	5	5	5	3	2	2	2	5	4	3	4	0	3	5	2	3	3
PM15	5	5	5	5	5	1	1	5	5	5	5	5	5	5	1	5	1	3	5	5
PM16	4	5	5	5	5	4	0	4	4	4	4	4	5	3	3	4	5	4	4	4
PM17	5	5	5	5	3	4	4	3	2	4	3	3	1	2	3	3	4	4	5	4
PM18	5	5	5	5	5	5	4	5	5	3	5	3	5	4	5	5	5	5	5	4
PM19	3	2	3	4	3	3	3	2	3	3	3	3	2	3	3	3	2	2	2	2
PM20	4	4	5	5	5	4	4	5	5	4	4	4	5	4	4	5	5	4	4	3

	Buildability factor of a building design																			
	Design							Resource				Flexibility				Site Layout and Safety				
ID	A1	A2	A3	A4	A5	A6	A7	B1	B2	B3	B4	C1	C2	C3	C4	D1	D2	D3	D4	D5
PM21	4	5	4	5	4	5	3	3	3	4	3	3	4	3	4	3	4	3	3	5
PM22	5	5	5	4	5	4	5	3	4	5	5	5	5	5	4	5	3	4	3	3
PM23	5	5	3	3	5	3	3	5	5	4	4	2	4	3	4	2	4	0	0	0
PM24	5	4	5	4	3	3	3	5	4	3	3	4	4	3	4	5	3	3	3	4
PM25	3	4	5	3	4	4	5	5	5	5	4	3	3	3	5	5	4	4	4	5
PM26	4	4	3	4	5	3	2	4	3	4	4	5	4	3	4	5	4	5	5	4
PM27	5	3	4	5	5	2	2	5	5	5	5	4	5	4	5	5	4	5	5	5
PM28	4	1	5	4	5	3	5	3	3	4	5	4	5	5	3	5	4	5	5	5
PM29	5	5	4	5	4	3	4	4	4	5	5	4	4	5	5	5	4	4	4	4
PM30	3	4	5	3	4	4	3	4	2	3	3	4	4	5	4	2	3	5	3	3
PM31	5	5	4	4	3	3	3	2	3	4	5	5	4	3	3	5	5	4	4	3
PM32	3	4	3	5	5	4	3	4	4	4	4	3	3	4	4	4	4	3	3	3
PM33	5	5	5	5	5	5	4	5	5	5	5	5	3	3	3	5	5	3	2	2
PM34	5	4	4	4	4	4	3	5	4	1	5	5	4	4	5	5	4	5	4	5
PM35	4	4	5	4	5	3	3	3	3	4	4	3	3	4	4	4	4	4	3	3

APPENDIX B
Summary of Subcriteria to Evaluate the Buildability Factors

Factors	Subcriteria	Current Practice of Design [Reference Projects]	Best Practice	Poor Practice
Standardization of designs	Repetition of floor layout	- The layouts of the ground floor are usually different from the other floors **[2, 4, 9, 10]** - The floor layouts of the basements are usually the same **[2, 9, 10]** - The floor layouts of the superstructure can vary for every 2 to 3 storeys according to the function (floors with the same function should have the same layouts) **[2, 6, 7, 10]** - The floor layouts of top storey (roof) can be different **[2, 10]** - Some types of building are exceptional (e.g. for shopping mall, theater or museum, the floor layouts can be different from one storey to another) **[6]**	- The floor layouts of the building above the ground floor are the same for every storey **[6, 8]**	- The floor layouts of the building are different for each storey **[4]**
	Repetition of floor height	- The height of the ground floor can be higher than the other storeys **[2, 7, 9, 10]** - The height of the basement floors should be the same **[5, 7, 9, 10]** - The height of the storeys above the ground should be the same for each function (e.g. optimal at 3.3 m) **[3, 5, 9, 10]**	- Most of the storeys have the same height (e.g. vary 2 to 3 times)	- The floor height of the building varies many times
	Section of building component	- There are 3 types (of sections) of columns for each floor (interior, exterior, corner/perimeter) **[1, 2, 5, 6, 9, 10]** - The sections of the columns (of the floor) are changed for every 3 storeys or more (the columns of the ground floor can be bigger than others) **[6, 8, 10]** - There are 3 types (of sections) of beams for each storey (e.g. primary beam for both directions, secondary beam, and cantilever), not including stairs and elevator **[2, 5, 6, 7, 8, 9, 10]** - The sections of beams (of each floor) are kept the same for every storey serving the same function **[6, 8, 9, 10]**	- There is only one type of section for each type of building component for each floor (e.g. columns, beam, slab, wall) - The section of every building component remains the same for every storey	- There are more than 3 types of sections for each type of building component for each storey **[4]** - The slab has an uneven top level - The slab has an uneven bottom level

		- The sections of concrete walls are kept the same for every storey **[10]** - The thickness of the floor varies according to function (e.g. car park 250 mm, normal 150 mm), and type of structure (e.g. RC 120 – 150 mm, or PT 200 – 250 mm) **[5, 10]** - The structure of slab does not change for the same floor (e.g. some parts use RC, some use PT) **[3]** - The types of slabs do not change from storeys to storeys **[3, 6]**		- The sections of the building components change for each storey
	Openings, block-outs	- The dimensions and the locations of most openings are kept the same for each floor **[1, 8]** - No architectural block-out of slab (e.g. indoor atrium patio) and wall **[6]**	- The dimensions and locations of most openings are kept the same for each floor - No architectural block-out of slabs and walls	- The dimensions and locations of the openings change from storeys to storeys - Have architectural block-outs of slabs and walls
	Use of design standard	- Using well-known design standards, such as BS, BAEL, Euro Code, and ACI (depends on company) **[1, 2, 5, 6, 8, 9, 10]** - Using the other design standards specified by owners or designers (acceptable as long as the design concepts are similar to the above ones) **[1, 6, 9, 10]**	- Use the design standards that the contractors have experience	- Use the design standards that the contractors do not have experience
Simplicity	Shape of building	- Not as important as standardization (i.e. the same designs for each floor are more important) **[6, 9]** - Rectangular is the most common shape, structure with straight lines is easier to construct **[2, 3, 7, 8, 9]** - Shapes composed of rectangular are acceptable (e.g. L shape, T shape) **[7, 9]**	- Building with simple rectangular shape	- Building with curved shape

		- Some buildings are exceptional (nonsymmetrical/irregular shape) (e.g. theater, shopping center) **[7, 6]**		
	Openings, block-outs	- Indoor architectural block-outs with simple shapes (e.g. indoor atrium patio) **[4, 6]** - Rectangular is the most common shape **[4, 8]** - Combined openings for MEP routings (i.e. the number of openings should be kept minimum) **[1, 8, 9]** - No opening through beam or concrete wall **[7, 9]** - No requirement of coring after concreting **[4, 9]**	- No architectural block-out (e.g. indoor atrium patio) - Combined openings (for MEP) through slabs - Openings (for MEP) with rectangular or round shape - No opening (for MEP) through beam or concrete wall	- Architectural block-oust (e.g. indoor atrium patio) with irregular shapes - Scatter openings (for MEP) through slabs - Openings (for MEP) with irregular shapes - Openings (for MEP) through beams or concrete walls
	Building components	- Not as important as standardization (i.e. it is more important to have the same shapes of building components for each floor) **[6, 9]** - No curved beam (horizontal) **[2, 8, 10]** - No inclined column **[6, 8]** - No high column (e.g. more than 6 meters) **[6]** - Each floor has at most 2 top levels (e.g. WC and balcony can be 5 cm lower than normal floor level, so that the concrete can be poured in one time) **[1, 2, 4, 5, 7]** - Each floor has the same bottom level **[2, 9]** - Using floor tile or screed to achieve differences in floor level **[9]**	- All building components with rectangular shape - Slab with even top and bottom level	- Some building components with irregular shapes - Column higher than 6 meters - Slab have more than 2 levels

		- The bottom level of each floor is kept the same, the top level varies (e.g. has a slope to drain water) **[7, 9, 10]** - For slab, the difficulty of construction is increased as follows (based on installation of formwork and rebar) Flat slab **[1, 5, 6, 10]** Drop panel **[3, 5, 6, 7, 10]** Band beam **[5, 6, 10]** RC slab with beam **[5, 6, 10]**		
Coordination between design documents	Checked by designers before submission to the owner for each design phase (schematic design, developed design, construction documents)	- Check coordination of drawings through meetings between architect, structural, and MEP engineers **[1, 2, 3, 4, 5, 6, 7, 8, 10]** - Check compliance of all the drawings with the owner's requirements and the regulations (e.g. requirements of function, public space, distance from the main road and surrounding buildings, total building height) **[6, 7, 8, 9, 10]** - Use BIM and 3D models to visualize the finished buildings and used materials **[1, 2, 5, 6]**	- Good coordination between design documents (all design disciplines are in the same group) **[2, 7]** - Coordination reviews by designers before submission to the owners for each design phase (e.g. preliminary study, schematic design, developed design, construction design) - Use BIM to coordinate and check the designs	- No coordination between design documents (e.g. some or all of the design disciplines are in different groups) - No or lack of coordination reviews by designers before submission to the owners for each design phase (e.g. preliminary study, schematic design, developed design, construction design)
	Double checked by the contractor before	- Check coordination between the architect, structural and MEP drawings (by overlap, combine and compare them) **[1, 4, 8, 9, 10]**	- Contractors check the coordination of design documents before construction	- Contractors cannot check the coordination of design documents

	construction (design documents for construction)	Between architect and structure: compare the building layouts (e.g. the perimeters of building, the symmetry of architectural and structural drawings), the gridlines, the sizes of columns, the heights of beams and ceilings, the openings **[4, 5, 6, 10]** Between structure and MEP: the locations of openings of slabs and beams, the locations of piping/wirings and walls (should be in the wall), the levels of ceilings and piping, the slopes of piping **[4, 5, 10]** Structure: the conflicts between structural components (e.g. beam & slab), the conflicts of space between structural components and users/devices (e.g. overhead space for walking and installing equipment), the conflicts between cables and rebar, the conflicts between rebar and rebar **[5]** - Check coordination between structural drawings and specifications (e.g. rebar dimensions, laps, covers, strengths of materials used, standard detailing) **[4, 5]** - Check structural drawings and calculation notes: the loads applied, the modeling (errors in design), the percentage of reinforcement, and the size of structural components **[2, 5]**	- Using BIM to check the designs	before construction (e.g. designs are not completed/finalized before construction)
Completion of design documents	Architectural, structural, MEP, and interior designs	- Drawings list **[2]** - Site location plan, block plan - Architectural drawings: master plans/layout plans, perspective plans, elevation plans, cross-section plans, floor layout plans, landscaping plans **[2, 4, 7, 10]** - Demolition plans **[2]** - Structural drawings **[3, 7, 10]** - MEP drawings **[4, 5, 7, 10]**	- Contractor has complete design documents before the construction **[2, 8]**	- Contractor has part of the design documents before the construction (e.g. design in phases) **[2, 6, 8]**

		- Drawings are not given in phases (e.g. foundation, basement, superstructure and architect) **[6, 8, 10]**		
Clarity of specifications	Scope of work	- State about the scope of work (e.g. the responsibilities of contractors, owner, designers, and consultant) **[2]**	- Clearly define the scope of work of each stakeholder	- Define the scope of work of each stakeholder with ambiguity
	Specifications of materials (structure, MEP, architect)	- Divided into sections (e.g. general specification, civil work, MEP work, architectural work) **[2, 7, 8, 10]** - Have reference to materials standards (e.g. ASTM, ISO, European Standard, Chinese Standard GB/JGJ) **[1, 6, 7]** - Specify the brand names, origins, and performances of materials **[2, 5, 7]** - Clearly state alternative materials instead of just using "or equivalent" **[2, 5, 7]** - Provide contact details of the suppliers for imported materials **[5, 7]** - Provide descriptions of how to use the materials **[4]** - Check with drawings to assure the completeness of specifications **[6, 10]**	- Specifications given according to different design disciplines - Specifications with references to materials standards - Specifications with product brand names and suppliers - The performances of all the materials used in the project are stated in the specifications	- Specifications given in general (mixed disciplines) - Specifications without reference to materials standards - Specifications without product brand name and supplier - Specifications missing some materials used in the project
	Tolerance	- Have reference to design standard (e.g. ACI, Eurocode) **[6, 10]** - Have tolerance for architectural components **[8, 10]** - Have tolerance for structural components **[10]** Verticality tolerance of building Tolerance of placing reinforcements Tolerance of concrete covers The verticality tolerance of columns The deflection tolerance of beams and slabs Tolerance for precast members	- Tolerance given for every type of work (e.g. architectural, structural, MEP, decoration)	- No tolerance mentioned

		Tolerance for cable placements and prestressing forces Tolerance of openings - Have tolerance for MEP installations **[8, 10]**		
	General notes and Typical details	- Architectural works (decoration) **[4, 7]** - Structural works **[2, 4, 7]** - MEP works **[4, 7]** - Site preparation, road, fence **[5, 2]** - Miscellaneous **[5, 2]**	- Clear and complete general notes and typical details	- Ambiguous and missing general notes and typical details
Underground construction (which affects the selection of construction methods, e.g. open excavation, open excavation and slope protection, sheet pile, bored pile, bored pile and strut)	Groundwater	- The groundwater level is below the excavation level (i.e. no water ingression) **[6, 8, 9, 10]** - The groundwater level is not affected by the water level of river/lake (i.e. no influence from seasonal change of water level of river/lake) **[6, 8, 9, 10]**	- Groundwater below the excavation level and remains stable	- Groundwater above the excavation level
	Type of soil	- Mostly clay **[3, 10]** - Silt (related to water ingression, angle of repose, stability of soil)	- Clay	- Sand or mud [7, 10] - Stone
	Surrounding	- Surrounding buildings are far from the construction site (i.e. allowing the use of noisy/vibratory machine) **[1, 2, 4, 6, 7, 8, 10]** - Surrounding buildings are at greater distance than the angle of repose (i.e. no requirement of soil retaining structures) **[1, 3, 4, 5, 6, 7, 10]**	- Allowing open excavation and use of noisy and vibratory machines	- Prohibiting open excavation and use of noisy and vibratory machines
	Location of site	- Located in the suburb/rural area (i.e. no restriction of transportation during the daytime) **[1, 6, 8, 10]**	- Located in the suburb/rural area	- Located in downtown
	Lower level of foundation	- The same lower level of the foundations (i.e. allowing the same level of excavation to avoid land slide) **[9]**	- The same lower level of the foundations (e.g. combined mat foundation and bottom basement)	- Uneven lower level of the foundations

Availability of materials	Availability (lead time)	- Available from many local suppliers (i.e. purchase period less than 2 weeks) Not difficult to find the RC materials **[2, 4, 5, 6, 10]** - Available from some local suppliers, but take some time to order (about 1 month) Rebar with section bigger than 25mm and PT cable **[10]** Precast components can be purchased or self-made (louver, finishing, plain slab, precast beam) **[1, 4, 5, 6, 7, 10]** Drywalls and curtain walls **[4, 6, 8, 10]** Structural steel members **[6]** - Available from local suppliers but cheaper to import if the quantity is large (take 2 to 3 months) **[1, 3, 5, 6, 7]**	- Owner supplies the materials - Available from many local suppliers (i.e. purchase period less than 1 week)	- Not available from local suppliers, need to import - Owners require to import/order from abroad
Availability of machines and equipment	Availability	- Available from many local suppliers or previous projects (i.e. used machine and equipment) **[1, 3, 5, 6, 7, 8, 10]** - Available from local dealers (for new machines and equipment) with stock **[1, 2, 5]** - Available from local dealers (new machines and equipment) without stock (i.e. order to import) (take 2 to 3 months) **[1, 5]**	- Owner supplies the machines - Own the machines and equipment - Available from many local suppliers (lead time less than 1 week)	- Not available from local suppliers - Owners require to import/order from abroad
Requirement of manpower	Types of structure	- Require less amount of labor (ranking in increasing order) **[4]** Steel structure (requires less amount of labor and less time to install) **[5, 6]** Partial precast structure (e.g. plain slab, precast beam, precast wall) (requires less amount of labor and less time to install) **[2, 6, 9]**	- Post-tension - Partial precast - RC - Allowing use of machines and equipment to install	- RC - Not allowing use of heavy machines and equipment to install

		Post-tensioned structure (require the same amount of labor, but take less time to install comparing to RC) **[3, 5, 6, 10]** Reinforced concrete structure **[1, 3, 5, 6]**		
	Schedule and size of work	- Sufficient project period **[3]** - Shorter schedule requires more labors **[5, 6, 7, 10]** - Larger project requires more labors **[5 6, 7, 10]**	- Sufficient time with some reserve time for delay	- Very tight schedule
Requirement of labor skills (based on experience)	Design to support skill available (structural)	- RC **[2, 3, 5, 6, 7, 9, 10]** - Post-tension **[2, 3, 5, 6, 7, 9, 10]** - Partial precast components **[5, 6, 9]**	- RC - Post-tension	- Precast - Steel [6, 9] - Composite [6]
	Design to support skill available (architectural) **[4, 7]**	- Brick wall - Drywall - Curtain wall / glass wall	- Simple architectural requirements (e.g. brick wall)	- Complicated/high architectural requirements
	Design to support skills available (MEP) **[7]**	- Installed by MEP suppliers **[2]** - Contractors outsource the installation process	- Installed by suppliers	- Installed by contractors that do not have experience
Design to suit site conditions	Site occupation (based on master plan)	- Building occupies less than 50% of total site area **[4, 6, 7]** - Have adequate space to install temporary facilities (e.g. site office, guard house, warehouse, stock yard, workshop, temp WC, accommodation for workers) (also depends on the size of work and schedule) **[2, 5, 6, 7]** - Have enough project period (depends on schedule, tighter schedule requires more space) **[6, 7]**	- Have abundant free space on site - Have loose schedule	- No free space on site - Not allowing installation of temporary facilities on site since the beginning of construction

	Site and soil investigation	- Complete and detailed soil investigation (to avoid the encounters of unexpected subsoil conditions, e.g. existing foundation, piping, wiring) **[1, 2, 5]**	- Thorough and accurate site investigation	- Poor site investigation
	Compliance with applicable regulations	- Maximum height of the building (according to zone) **[3]** - Distance from main public road (25 m from the central line of the main road) **[1, 2]**	- Comply with all applicable regulations	- Violate some regulations
Design to support transportation of materials and labors	Adjacency to surrounding buildings	- Have at least 2 meters distance from surrounding building (to install scaffolding) **[1, 8, 9, 10]** - Should have 4 meters distance from surrounding building (so that the vehicle can travel around) **[1, 2, 3, 4, 9, 10]**	- Have sufficient distance which allows the vehicles to travel around the building	- Not allowing vehicles to travel around the site - Not allowing installation of scaffolding outside the building
	Tower crane coverage	- One or more tower cranes can cover entire site **[1, 7]** - One or more tower cranes can cover most of the site **[3, 6]**	- Site under full coverage of tower crane	- Not allowing installation of tower crane - Very limited coverage of tower crane
	Proximity to main road	- One side of the site is next to the main road (allowing heavy trucks to access the site) **[5, 8]** - Have an access road to the site (allowing access of heavy trucks) **[5, 8]**	- One or more sides of the site are next to main road	- Not allowing heavy vehicles to access the site (no adequate access road to the site)

APPENDIX C
Results of Application on 11 Building Projects

Application of the AHP Model on Building Construction Projects to Assess the Buildability

Buildability Criteria	Local	Global	Project 1A			Project 1B			Project 1C		
Buildability Factor	weights	weights	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents	0.274										
Standardization	0.165	0.045	G	0.261	0.012	F	0.063	0.003	A	0.129	0.006
Simplicity	0.111	0.030	G	0.261	0.008	A	0.129	0.004	G	0.261	0.008
Coordination	0.193	0.053	A	0.129	0.007	P	0.034	0.002	A	0.129	0.007
Completion	0.249	0.068	F	0.063	0.004	G	0.261	0.018	P	0.034	0.002
Clear specification	0.164	0.045	G	0.261	0.012	G	0.261	0.012	A	0.129	0.006
Underground construction	0.118	0.032	G	0.261	0.008	A	0.129	0.004	A	0.129	0.004
Resources	0.377										
Material	0.230	0.087	G	0.261	0.023	A	0.129	0.011	G	0.261	0.023
Machine and equipment	0.215	0.081	G	0.261	0.021	G	0.261	0.021	G	0.261	0.021
Manpower	0.223	0.084	F	0.063	0.005	A	0.129	0.011	A	0.129	0.011
Labour skill	0.332	0.125	F	0.063	0.008	A	0.129	0.016	G	0.261	0.033
Site Layout	0.348										
Suit site condition	0.466	0.162	F	0.063	0.010	A	0.129	0.021	G	0.261	0.042
Support transport	0.534	0.186	G	0.261	0.049	A	0.129	0.024	G	0.261	0.049
Total Scores		0.999			0.167			0.146			0.328
Percentage of Best Design					32.5%			28.6%			63.8%
Expectation of Respondent					Average			Average			Good
Interpretation of Score *					Average			Average			Good

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

Buildability Criteria	Project 2A			Project 2B			Project 3		
Buildability Factor	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents									
Standardization	G	0.261	0.012	G	0.261	0.012	G	0.261	0.012
Simplicity	G	0.261	0.008	G	0.261	0.008	G	0.261	0.008
Coordination	G	0.261	0.014	A	0.129	0.007	A	0.129	0.007
Completion	A	0.129	0.009	G	0.261	0.018	O	0.513	0.035
Clear specification	A	0.129	0.006	A	0.129	0.006	O	0.513	0.023
Underground construction	G	0.261	0.008	A	0.129	0.004	O	0.513	0.017
Resources									
Material	G	0.261	0.023	G	0.261	0.023	O	0.513	0.044
Machine and equipment	A	0.129	0.010	G	0.261	0.021	O	0.513	0.042
Manpower	G	0.261	0.022	A	0.129	0.011	O	0.513	0.043
Labour skill	G	0.261	0.033	G	0.261	0.033	G	0.261	0.033
Site Layout									
Suit site condition	G	0.261	0.042	G	0.261	0.042	G	0.261	0.042
Support transport	G	0.261	0.049	G	0.261	0.049	G	0.261	0.049
Total Scores			0.235			0.232			0.354
Percentage of Best Design			45.8%			45.3%			69.1%
Expectation of Respondent			Good to Average	G		o od to Average			Good
Interpretation of Score *			Average			Average			Good

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

Buildability Criteria	Project 4A			Project 4B			Project 4C			Project 5		
Buildability Factor	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents												
Standardization	A	0.261	0.006	G	0.261	0.012	A	0.129	0.006	G	0.261	0.012
Simplicity	A	0.261	0.004	F	0.063	0.002	F	0.063	0.002	O	0.513	0.016
Coordination	O	0.513	0.027	G	0.261	0.014	A	0.129	0.007	O	0.513	0.027
Completion	G	0.261	0.018	A	0.129	0.009	F	0.063	0.004	G	0.261	0.018
Clear specification	G	0.261	0.012	O	0.513	0.023	A	0.129	0.006	O	0.513	0.023
Underground construction	G	0.261	0.008	G	0.261	0.008	P	0.034	0.001	O	0.513	0.017
Resources												
Material	O	0.513	0.044	A	0.129	0.011	G	0.261	0.023	G	0.261	0.023
Machine and equipment	O	0.513	0.042	G	0.261	0.021	G	0.261	0.021	O	0.513	0.042
Manpower	O	0.513	0.043	F	0.063	0.005	A	0.129	0.011	O	0.513	0.043
Labour skill	G	0.261	0.033	G	0.261	0.033	G	0.261	0.033	F	0.063	0.008
Site Layout												
Suit site condition	G	0.261	0.042	F	0.063	0.010	P	0.034	0.006	G	0.261	0.042
Support transport	G	0.261	0.049	A	0.261	0.024	F	0.063	0.012	O	0.513	0.095
Total Scores			0.328			0.172			0.130			0.365
Percentage of Best Design			63.9%			33.6%			25.4%			71.2%
Expectation of Respondent			Good			Average			Average			Good
Interpretation of Score *			Good			Average			Average			Good

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

Buildability Criteria	Project 6A			Project 6B			Project 6C			Project 6D		
Buildability Factor	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents												
Standardization	O	0.513	0.023	G	0.261	0.012	A	0.129	0.006	G	0.261	0.012
Simplicity	G	0.261	0.008	G	0.261	0.008	G	0.261	0.008	G	0.261	0.008
Coordination	O	0.513	0.027	A	0.129	0.007	A	0.129	0.007	G	0.261	0.014
Completion	O	0.513	0.035	G	0.261	0.018	A	0.129	0.009	F	0.063	0.004
Clear specification	O	0.513	0.023	G	0.261	0.012	G	0.261	0.012	A	0.129	0.006
Underground construction	G	0.261	0.008	F	0.063	0.002	A	0.129	0.004	F	0.063	0.002
Resources												
Material	O	0.513	0.044	G	0.261	0.023	G	0.261	0.023	G	0.261	0.023
Machine and equipment	O	0.513	0.042	G	0.261	0.021	G	0.261	0.021	G	0.261	0.021
Manpower	O	0.513	0.043	G	0.261	0.022	G	0.261	0.022	G	0.261	0.022
Labour skill	G	0.261	0.033	G	0.261	0.033	G	0.261	0.033	G	0.261	0.033
Site Layout												
Suit site condition	G	0.261	0.042	A	0.129	0.021	A	0.129	0.021	G	0.261	0.042
Support transport	O	0.513	0.095	A	0.129	0.024	A	0.129	0.024	A	0.129	0.024
Total Scores			0.424			0.201			0.189			0.210
Percentage of Best Design			82.8%			39.3%			36.8%			41.0%
Expectation of Respondent			Outstanding			Good			Average			Good
Interpretation of Score *			Good			Average			Average			Average

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

Buildability Criteria	Project 7			Project 8			Project 9		
Buildability Factor	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents									
Standardization	G	0.261	0.012	O	0.513	0.023	O	0.513	0.023
Simplicity	A	0.129	0.004	O	0.513	0.016	O	0.513	0.016
Coordination	G	0.261	0.014	G	0.261	0.014	G	0.261	0.014
Completion	G	0.261	0.018	O	0.513	0.035	G	0.261	0.018
Clear specification	G	0.261	0.012	G	0.261	0.012	G	0.261	0.012
Underground construction	G	0.261	0.008	P	0.034	0.001	G	0.261	0.008
Resources									
Material	G	0.261	0.023	O	0.513	0.044	A	0.129	0.011
Machine and equipment	G	0.261	0.021	O	0.513	0.042	G	0.261	0.021
Manpower	G	0.261	0.022	O	0.513	0.043	G	0.261	0.022
Labour skill	O	0.513	0.064	F	0.063	0.008	A	0.129	0.016
Site Layout									
Suit site condition	G	0.261	0.042	P	0.034	0.006	G	0.261	0.042
Support transport	G	0.261	0.049	P	0.034	0.006	A	0.129	0.024
Total Scores			0.288			0.249			0.227
Percentage of Best Design			56.2%			48.7%			44.4%
Expectation of Respondent			Good			Average			Good
Interpretation of Score *			Good			Average			Average

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

Buildability Criteria	Project 10			Project 11A			Project 11B		
Buildability Factor	Rating	Score	× GW	Rating	Score	× GW	Rating	Score	× GW
Design Documents									
Standardization	O	0.513	0.023	G	0.261	0.012	G	0.261	0.012
Simplicity	O	0.513	0.016	G	0.261	0.008	A	0.129	0.004
Coordination	G	0.261	0.014	P	0.034	0.002	P	0.034	0.002
Completion	G	0.261	0.018	A	0.129	0.009	A	0.129	0.009
Clear specification	G	0.261	0.012	A	0.129	0.006	G	0.261	0.012
Underground construction	G	0.261	0.008	G	0.261	0.008	G	0.261	0.008
Resources									
Material	A	0.129	0.011	G	0.261	0.023	G	0.261	0.023
Machine and equipment	G	0.261	0.021	G	0.261	0.021	G	0.261	0.021
Manpower	G	0.261	0.022	F	0.129	0.005	A	0.129	0.011
Labour skill	A	0.129	0.016	O	0.261	0.064	G	0.261	0.033
Site Layout									
Suit site condition	A	0.129	0.021	G	0.261	0.042	O	0.513	0.083
Support transport	A	0.129	0.024	O	0.513	0.095	O	0.513	0.095
Total Scores			0.206			0.296			0.312
Percentage of Best Design			40.2%			57.6%			60.9%
Expectation of Respondent			Good			Good			Good
Interpretation of Score *			Good			Good			Good

* Score: = 0.512 Outstanding; >= 0.261 Good; >= 0.129 Average; >=0.063 Fair; >= 0.034 Poor

VITA

Heng Ly was born on 4th October 1989, in Phnom Penh, Cambodia. He finished his secondary school at Duan Hua and Toul Svay Prey Secondary School in 2004, and high school at You Kon Thor High School in 2007. He then continued his Bachelor Degree in Engineering at Institute of Technology of Cambodia (ITC) and in Management at University of Cambodia (UC). He obtained his Bachelor of Business Management in 2011 and the Bachelor of Civil Engineering in 2012. He took some training related to civil engineering and a few internships in construction companies before graduation. During the study of the final years at ITC (2012), he was awarded a scholarship from ASEAN University Network/Southeast Asia Engineering Education Development Network (AUN/SEED-Net) program to pursue his Master's Degree in Construction Engineering and Management at Chulalongkorn University, Thailand.