EMERGING MATH-RELATED CRITICAL THINKING THEORY IN CIVIL ENGINEERING PRACTICE

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Engineering Education)

School of Graduate Studies
Universiti Teknologi Malaysia

JUNE 2016

ACKNOWLEDGEMENT

In the name of Allah, the Most Beneficent, the Most Merciful.

I would like to express my sincere appreciation to several wonderful people who have made this research and the completion of this thesis possible.

My deepest gratitude goes first and foremost to my supervisors, Professor Dr. Shahrin bin Mohammad, Professor Dr. Mohd Salleh bin Abu and Dr. Mahani binti Mokhtar for their invaluable advice and guidance. I am particularly grateful for the trust and confidence they have put in me. They gave me inspiring support in the development and completion of this study. They walked with me through all the stages of this study with their enthusiastic encouragement and enlightening instruction until this thesis reached its present form. Words seem so inadequate to express my gratitude to them.

I am also indebted to Jabatan Pendidikan Politeknik and Malaysian Ministry of Higher Education for providing me tremendous opportunity by funding my doctoral program. My special thanks are extended to the School of Graduate Studies and Centre for Engineering Education (CEE), especially to the director of CEE, Associate Professor Dr. Khairiyah binti Mohd. Yusof, and all the staff who have provided assistance at various occasions. I am also appreciative of the staff of the both civil consultancy firms for their great cooperation with the collection of my data.

Finally, but most importantly, to my beloved family and marvelous friends, I really appreciate their continuing support, patience and prayers. They are my inspiration and they inspired this study. Their understanding and caring throughout this journey allowed me to immerse myself in my study with relish.

ABSTRACT

Engaging critical thinking and mathematical thinking as a two-dimensional perspective in civil engineering practice is consistent with engineering criteria of the Engineering Accreditation Council, Board of Engineers Malaysia. Thus, it is timely and crucial to inculcate critical thinking and mathematical thinking into the current engineering education. Unfortunately, information about the interrelation between these two types of thinking in real engineering practice is not well established in literature. Therefore, this thesis presents an empirical research using a modified grounded theory approach which studied critical thinking and mathematical thinking in real-world engineering practice. The study focused on developing a substantive theory pertaining to these two types of thinking. Data were generated from semi-structured interviews with eight practicing civil engineers from two engineering consultancy firms. Multiple levels of data analysis comprising open coding, axial coding and selective coding were used. The emerging theory, Math-Related Critical Thinking consists of six essential processes of justifying decision reasonably in engineering design process, namely complying requirements, forming conjectures/assumptions, drawing reasonable conclusion, defending claims with good reasons, giving alternative ways/solutions and selecting/pursuing the right approach. The theory explains the interrelation and interaction among the pertinent elements through the process of justifying decision reasonably in dominating orientation. The study contributes useful information in the form of a substantive theory for engineering education, which is aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council.

ABSTRAK

Penglibatan pemikiran kritis dan pemikiran matematik sebagai suatu perspektif dua dimensi dalam amalan kejuruteraan awam adalah selaras dengan kriteria kejuruteraan bagi Majlis Akreditasi Kejuruteraan, Lembaga Kejuruteraan Malaysia. Oleh itu, masa kini merupakan masa yang bertepatan dan penting untuk memupuk pemikiran kritis dan pemikiran matematik dalam pendidikan kejuruteraan. Namun begitu berdasarkan kajian lepas, maklumat tentang hubungkait antara kedua-dua jenis pemikiran ini dalam realiti amalan kejuruteraan masih belum mantap. Oleh itu, kajian ini menjelaskan tentang satu kajian empirikal yang menggunakan pendekatan *modified grounded theory* untuk mengkaji tentang pemikiran kritis dan pemikiran matematik dalam realiti amalan kejuruteraan. Kajian ini memberi tumpuan kepada pembangunan teori substantif yang berkaitan dengan kedua-dua jenis pemikiran tersebut. Data diperoleh daripada temu bual separa berstruktur bersama lapan jurutera awam dari dua firma perundingan kejuruteraan. Pelbagai peringkat analisis data yang terdiri daripada pengekodan terbuka, pengekodan paksi dan pengekodan terpilih telah digunakan. Teori yang terhasil iaitu *'Math-Related Critical Thinking'* terdiri daripada enam proses penting yang menjustifikasi keputusan secara munasabah dalam proses reka bentuk kejuruteraan iaitu mematuhi keperluan, membuat jangkaan/andaian, membuat kesimpulan yang munasabah, mempertahankan penyataan dengan alasan yang baik, memberikan cara/penyelesaian alternatif dan memilih/mengikuti pendekatan yang betul. Teori ini menjelaskan hubungkait dan interaksi di kalangan elemen penting melalui proses menjustifikasi keputusan secara munasabah dalam mendominasi orientasi. Kajian ini menyumbang maklumat yang berguna dalam bentuk teori substantif untuk pendidikan kejuruteraan, sejajar dengan sasaran pencapaian program kejuruteraan yang ditetapkan oleh Majlis Akreditasi Kejuruteraan.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ABET	-	Accreditation Board for Engineering and Technology
ASCE	-	American Society for Civil Engineers
BEM	-	Board of Engineers Malaysia
BOK2	-	Body of Knowledge 2nd Edition
CAN	-	Critical Thinking - Analysis
CDA	-	Critical Thinking - Analyticity
CDC	-	Critical Thinking - Confidence
CDI	-	Critical Thinking - Inquisitiveness
CDM	-	Critical Thinking - Open-mindedness
CDO	-	Critical Thinking - Orderliness
CDR	-	Critical Thinking – Maturity of Judgment
CDT	-	Critical Thinking - Truth-seeking
CE	-	Civil Engineering
CEV	-	Critical Thinking - Evaluation
CEX	-	Critical Thinking - Explanation
CGR	-	Conditional Relationship Guide
CGT	-	Classical Grounded Theory
CIF	-	Critical Thinking - Inference
CIP	-	Critical Thinking - Interpretation
CSR	-	Critical Thinking - Self-reflection
CT	-	Critical Thinking
CTD	-	Critical Thinking - Dispositions
CTS	-	Critical Thinking - Core Skills
EAC	-	Engineering Accreditation Council
EDP	-	Engineering Design Process
EM	-	Engineering Mathematics
EP	-	Engineering Practice

GT	-	Grounded Theory
HOT	-	Higher Order Thinking
IDP	-	Integrated Design Project
MBA	-	Mathematical Thinking – Beliefs and Affects
MKB	-	Mathematical Thinking – Knowledge Base
MMC	-	Mathematical Thinking – Monitoring and Control
MMP	-	Mathematical Thinking – Practices
MPS	-	Mathematical Thinking – Problem Solving Strategies
MRCT	-	Math-Related Critical Thinking
MT	-	Mathematical Thinking
MTC	-	Aspects of Cognition
PE	-	Pertinent Elements
PS	-	Purposive Sampling
QDA	-	Qualitative Data Analysis
RCM	-	Reflective Coding Matrix
RO	-	Research Objective
RQ	-	Research Question
TS	-	Theoretical Sampling

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

In this rapidly changing world, it is seen that knowledge and technology are expanding exponentially. Issues and problems such as global warming, pollution, environment, constructions, economic or political crisis are becoming more challenging, complex and increasingly threatening. Since the information about global issues and problems is readily made available and also changed rapidly, the utilization of such information in making reliable decisions is important to succeed in managing the challenges (Lau, 2011). Inevitably, the current global phenomena of knowledge explosion and technology advancement have impacted the engineering profession and engineering education.

Modern construction is progressively a process of assembly. Knowledge and technology bring about new methods and forms of construction. Although without doubt it removes some of the risks inherent in building, it also creates a series of new problems, most particularly with coordination and interfacing (Watts Group Limited, 2015). As design practice improves and performance standards become more thorough and stricter, buildings are becoming more finely engineered. However, it brings potential issues as the finer a structure is engineered, the physics of a building becomes more critical (Watts Group Limited, 2015).

A report written by Suffian (2013) gives an overview of the common maintenance problems and building defects on civil and structural elements at the Social Security Organisation (SOCSO) buildings across Malaysia. Many buildings in

Malaysia are designed with a flat roof concept rather than traditional pitched roof in order to suit a modern concept of design and ease of maintenance (Suffian, 2013). Due to the Malaysian's climate which is hot and humid throughout the year with relatively high annual average rain intensity of 250 cm, the problem that mostly associates with the flat roof is a waterproofing-related issue.

The challenge here is how to balance the technology and innovation with realism. There is a need to offer better solutions to most of the issues, challenges and changes for the betterment of mankind. Relatively, none of the construction failures recorded was genuinely new due to a failure somewhere along the line to recognize and apply a few essential principles (Watts Group Limited, 2015). Defects and failures can be reduced if more attention is given to matters related to coordination and interfacing between different materials and products. For instance, most things conform notably to the laws of gravity, temperature, pressure and corrosion. Thus, a basic appreciation of some basic scientific principles and a substantial dose of common sense will minimize the occurrence of the failures (Watts Group Limited, 2015). Moreover, the emerging issues in the engineering world have revealed many pivotal characteristics of ill-structured problems which call for engineers to think critically (Felder, 2012).

In view of that, the National Academy of Engineering (2005) states that the future engineering curriculum should be built around developing skills such as analytical and problem-solving skills rather than teaching available knowledge. Emphasis should be laid on teaching students about methods to solutions rather than giving the solutions (National Academy of Engineering, 2005). Consequently, another related issue arises as to whether the current engineering curriculum prepares students with the required critical thinking knowledge, skills and values to face such challenges (Felder, 2012; Norris, 2013).

The current teaching and learning approaches as well as the assessment method should also be reviewed (Felder, 2012). The new engineering curriculum must take into account that in the future students will learn in a completely different way (National Academy of Engineering, 2005). In practice, it appears that the engineering departments tend to develop curricula with preset or predicted problems expected to be encountered. In doing so, the emphasis is given on knowledge rather than skills.

On the contrary the future engineering curriculum should have more emphasis on developing skills such as analytical, problem-solving and design skills rather than focusing merely on available knowledge and solutions. The focus should be on preparing the future engineers to be creative and flexible, to be curious and imaginative (National Academy of Engineering, 2005). Engineers must be prepared to solve unknown problems and not for addressing assumed scenarios. Therefore, infusing real engineering problems and experiences into engineering curriculum is timely and crucial (Felder, 2012).

For years, critical thinking and mathematical thinking have been regarded as integral components of engineering learning: The American Society for Civil Engineering in the body of knowledge (BOK2 ASCE, 2008) has explicitly noted mathematics as one of the four foundational legs besides basic science, social science and humanities, which supports the future technical and professional practice education of civil engineers. Therefore, mathematical thinking has been used as an essential learning tool to facilitate the learning of engineering subjects. In addition, reports of Engineer 2020 (National Academy of Engineering, 2005) and Millennium Project (Duderstadt, 2008) reveal critical thinking as an essential element of the key attributes of an engineer.

Within the context of solving civil engineering problems, engaging critical thinking and mathematical thinking as a two dimensional perspective weaved together, is a way of approaching the engineering criteria of Engineering Accreditation Council, Board of Engineers Malaysia (EAC-BEM, 2012). The criteria highlight the required attributes of prospective engineers such as applying mathematical and engineering knowledge, analyzing and interpreting data, formulating and solving engineering problems in engineering program outcomes (ABET, 2014; EAC-BEM, 2012). The EAC-BEM (2012) also emphasizes critical thinking development and evidence-based decision making in curriculum. Thus, it is deemed relevant and significant to conduct a study to understand the interrelation and interaction between critical thinking and mathematical thinking related to the cognitive activities and aspects of cognition in the civil engineering practices (Radzi, Abu, Mohammad & Abdullah, 2011). Therefore, the interrelation and interaction among pertinent elements of these two types of thinking in real-world engineering practice needs to be explored, studied and established.

The use of the words ‘thinking’ and ‘cognition’ are often interchangeable. In the most general sense, thinking is collectively defined as a mental process (Geertsen, 2003). Matlin (2009) has defined cognition as mental activity that describes the acquisition, storage, transformation, and use of knowledge. In the same view, mental process or cognitive function is all the things that individuals can do with minds such as perception, memory, thinking, imagery, reasoning, decision making and problem solving. Accordingly, if cognition operates every time acquiring some information via placing it in storage, transforming the information and using it, then cognition definitely comprises a large scope of mental processes (Matlin, 2009).

Scholars and practitioners have consensus that teaching of thinking has a distinct value and significance in preparing citizens of the future generation (Karabulut, 2009). According to National Academy of Engineering (2005), teaching engineers to think analytically is more important than helping them memorize algebra theorems. It is the consensus of the experts in the Delphi Project (Facione, 1990) to include analysis as one of the core skills to critical thinking. The close interrelation between these analysis and critical thinking is as though a deficiency in the analytical ability would significantly have negative impact in critical thinking. Therefore, these two skills cannot be discussed as a separate entity and wherever appropriate, both skills do appear concurrently. Intrinsically, problem solving requires a person to be critical to solve problems effectively and meaningfully. Thus, it is occasionally mentioned alongside critical thinking when the need arises.

This chapter provides an introduction to the research work presented in this thesis. It describes the research background which explains the background of the research problem. It introduces the reader to the key features of this research such as the research goals, objectives and questions. It presents the conceptual framework of the research. It also informs the significance of this study as well as the scope and delimitations of this research. In addition, it provides an overview of the research approach as well as of the results obtained. This chapter has been organized as portrayed in Figure 1.1.

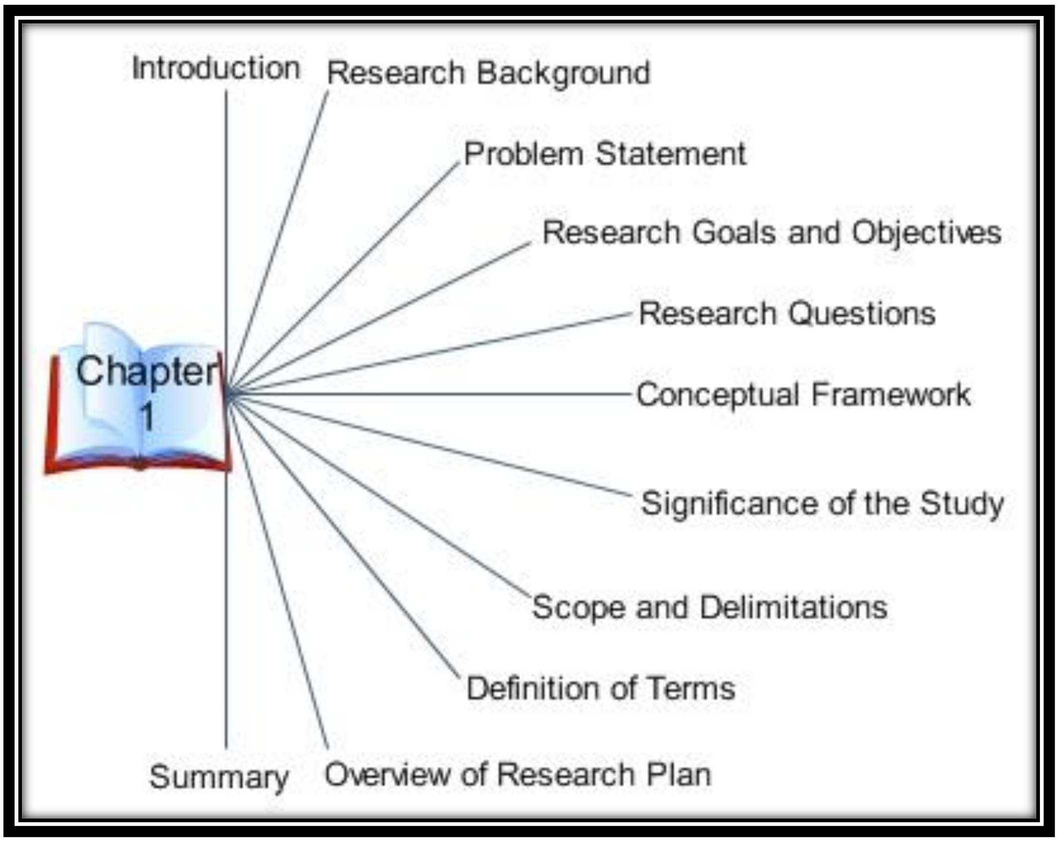


Figure 1.1: Thematic Structure of Chapter 1

1.2 Research Background

Program outcomes listed in the manual of Engineering Accreditation Council, Board of Engineers of Malaysia (EAC-BEM, 2012) emphasize competencies of engineering graduates in dealing with complex engineering problems, such as having ability to identify, formulate, analyze and apply mathematical knowledge to engineering problems. The manual also puts emphasis on providing students with ample opportunities for critical thinking skills development and evidence-based decision making (EAC-BEM, 2012). It clearly indicates the needs of adaption in cultivating required attributes according to the different disciplines of engineering fundamentals and specialization.

In addition, complex real-life problems often demand complex solutions, which are obtained through higher level thinking processes (King, Goodson & Rohani, 2008). Unfortunately, the absence of clear descriptions delineating critical thinking skills for the civil engineering courses and compounded by the varied interests and needs of each university can lead to various ways of expressing the critical thinking skills requirements (McGowan & Graham, 2009).

A research conducted at a Malaysian private university has proven that among the seven elements of soft skills to be implemented at all higher learning institutions in Malaysia, critical thinking and problem solving skills have been placed as the most important soft skills to be taught to engineering students (Idrus, Dahan & Abdullah, 2010). However, the finding from the research has also revealed there is a difference in perceptions among the lecturers and students in the way they perceived the integration of critical thinking and problem solving skills in the teaching of technical courses (Idrus et al., 2010). In other words, there is congruence in perception between the lecturers and students on the importance of critical thinking skills but in terms of implementation, it is not clear to the students.

A study on faculty members, who had improved teaching significantly over at least a three-year period, discovers that one of the factors leading to better teaching performance is to emphasize clear learning outcome and the lecturers' expectations to the students (McGowan & Graham, 2009). Furthermore, one of the activities to promote the establishment of an effective learning environment for process skill development is to identify the skills students need to develop, to include the skills in the course syllabus and to communicate the skills' importance to the students (Woods, Felder, Rugarcia & Stice, 2000). This is to ensure the students understand the relevance of the skills with professional success. It can be done by having discussion about the skills at the same level of seriousness and enthusiasm when the technical content of the course is presented. Therefore, it is important to have clear understanding on the relevance between critical thinking and engineering courses, which is currently still lacking in relation to the real-world civil engineering practice.

Similarly, critical thinking is recognized as an important skill and a primary goal of higher education. However, comprehensive studies of critical thinking and an understanding of what critical thinking is, within the context of civil engineering are hardly to be obtained from the extant literature (Douglas, 2012a, 2012b; Douglas, 2006).

Critical thinking is a form of higher-order thinking skills (King et al., 2008). Teaching higher order thinking affords students with pertinent life skills and serves supplementary benefit of helping the students to improve content knowledge, lower order thinking, and self-esteem (King et al., 2008). Looking back to the past years, the Malaysian education system emphasized more the development of strong content knowledge, especially in subjects such as sciences, mathematics and language. It seemed fulfilling and in parallel with the fundamental objective of any education system, which is to ensure the knowledge and skills required for having successful life is well-being cultivated.

However, as mentioned in the Malaysian Education Blueprint (Ministry of Education Malaysia, 2012), awareness on the global recognition that the emphasis is no longer concentrate merely on the needs of knowledge, but also on developing higher-order thinking skills. Ability to think critically is a part of thinking skills in appreciating diverse views. It is one of six primary attributes for students that anchored on by the higher education system, as mentioned in Malaysia Education Blueprint 2015-2025 (Higher Education) (Ministry of Education Malaysia, 2015). Malaysia needs graduates with transferrable skills such as critical and creative thinking and problem solving skills to deal with present and future demands (Ministry of Education Malaysia, 2015).

Another aspect emphasized in the engineering program outcomes is the application of mathematical knowledge in the problem analysis and to the solution of complex engineering problems (ABET, 2014; EAC-BEM, 2012). According to BOK2 ASCE (2008) a technical core of knowledge and breadth of coverage in mathematics, and the ability to apply it to solve engineering problems, are essential skills for civil engineers, in parallel with the fact that all areas of civil engineering rely on mathematics for the performance of quantitative analysis of engineering systems.

Therefore, mathematics has a vital role in the fundamental of engineering educations for the 21st century engineers (Henderson & Broadbridge, 2007; Uysal, 2012). In addition, a central component in current reforms in mathematics and science studies worldwide is the transition from the traditional dominant instruction which focuses on algorithmic cognitive skills towards higher order cognitive skills, particularly critical thinking (Aizikovitsh & Amit, 2009, 2010; Ministry of Education Malaysia, 2012).

Furthermore, a review into the American Society for Civil Engineering in the body of knowledge reveals that the cognitive level of achievement has been generically described based on the Bloom's taxonomy and the associated descriptors for the civil engineering courses (BOK2 ASCE, 2008). However, there are no extensive descriptions delineating critical thinking elements for the engineering mathematics courses. Therefore, to have an empirical insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking becomes the main goal of this study. In order to be within a reasonable confinement, this study refers to the perspectives of Facione for critical thinking (Facione, Facione & Giancarlo, 2000; Facione, 1990, 2007, 2013) and Schoenfeld for mathematical thinking (Schoenfeld, 1985, 1992).

Stated in the National Academy of Engineering (National Academy of Engineering, 2005), engineering education must be realigned, refocused and reshaped to promote attainment of the characteristics desired in practicing engineers. This must be executed in the context of an increased emphasis on the research base underlying conduct of engineering practice and engineering education. Furthermore, as a profession, engineering is undergoing transformative evolution where the fundamental engineering processes remain the same but the domains of application are rapidly expanding (National Academy of Engineering, 2005). Thus, there is a need to develop enhanced understanding of models of engineering practice in this evolving environment.

Equally important, ability to think independently is essential to succeed in today's globally connected and rapidly evolving engineering workplace (National Academy of Engineering, 2012) . Besides the existing excellent technical education, infusing real engineering problems and experiences into engineering education to give engineering students exposure to real engineering is timely and crucial (Felder, 2012).

Moreover, the current scenario to facilitate engineering students' learning of engineering mathematics seems to be inadequate in enhancing students' ability to apply the mathematical knowledge and skills analytically and critically (Felder, 2012). Consequently, it makes the transfer of learning across the students area of study does not occur as efficiently as would have expected (Rahman, Yusof, Ismail, Kashefi & Firouzian, 2013; Rebello & Cui, 2008; Townend, 2001; Yusof & Rahman, 2004). The transfer of knowledge remains problematic and needs to find ways for better integrating mathematics into engineering education (Rahman et al., 2013). This approach should support and enhance mathematical thinking and create the necessary bridge to link mathematics to problem solving in engineering (Rahman et al., 2013).

On top of that, findings from the previous study have shown congruence between critical thinking and mathematical thinking (Radzi et al., 2011). The study carried out at a civil engineering consultancy firm revealed some prevalent trends of engineering workplace problems and challenges. It discloses many characteristics of ill-structured problems in the nature of engineering workplace contexts required civil engineers to think critically in search of the best solutions or alternatives. On closer analysis using constant comparative method, findings seem to exhibit considerable forms of congruence which calls for both critical thinking and mathematical thinking in chorus, in order to deal with these workplace problems and challenges effectively (Radzi, Mohamad, Abu & Phang, 2012).

The findings provide subtle but crucial indicator of the existence of a close relevance between these two perspectives of thinking in engineering workplace context. However, there is no further study has been done to explore and understand in depth how these two types of thinking are being used in the engineering workplace. Therefore, to have insights into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in the engineering practice is thought to be helpful to lubricate and accelerate the process of understanding, applying and transferring mathematical knowledge into engineering education.

Overview of the research background is depicted in Figure 1.2. The figure visualizes all aspects contributing to the formulation of research problem as mentioned earlier. It summarizes the needs to explore critical thinking and mathematical thinking in civil engineering workplace into three factors as follows:

a) Inadequacy/Gap

This factor covers two main aspects of the research gap: i) incomplete work in the previous research and ii) lack of study, literature and theory on the interrelation and interaction between critical thinking and mathematical thinking.

b) Engineering Criteria

The criteria refers to EAC-BEM (2012), ABET (2014) and BOK2 ASCE (2008).

c) Motivation for Research

It refers to the personal working experience of the researcher.

The formulated research problem is presented in a statement of problem in the following section.

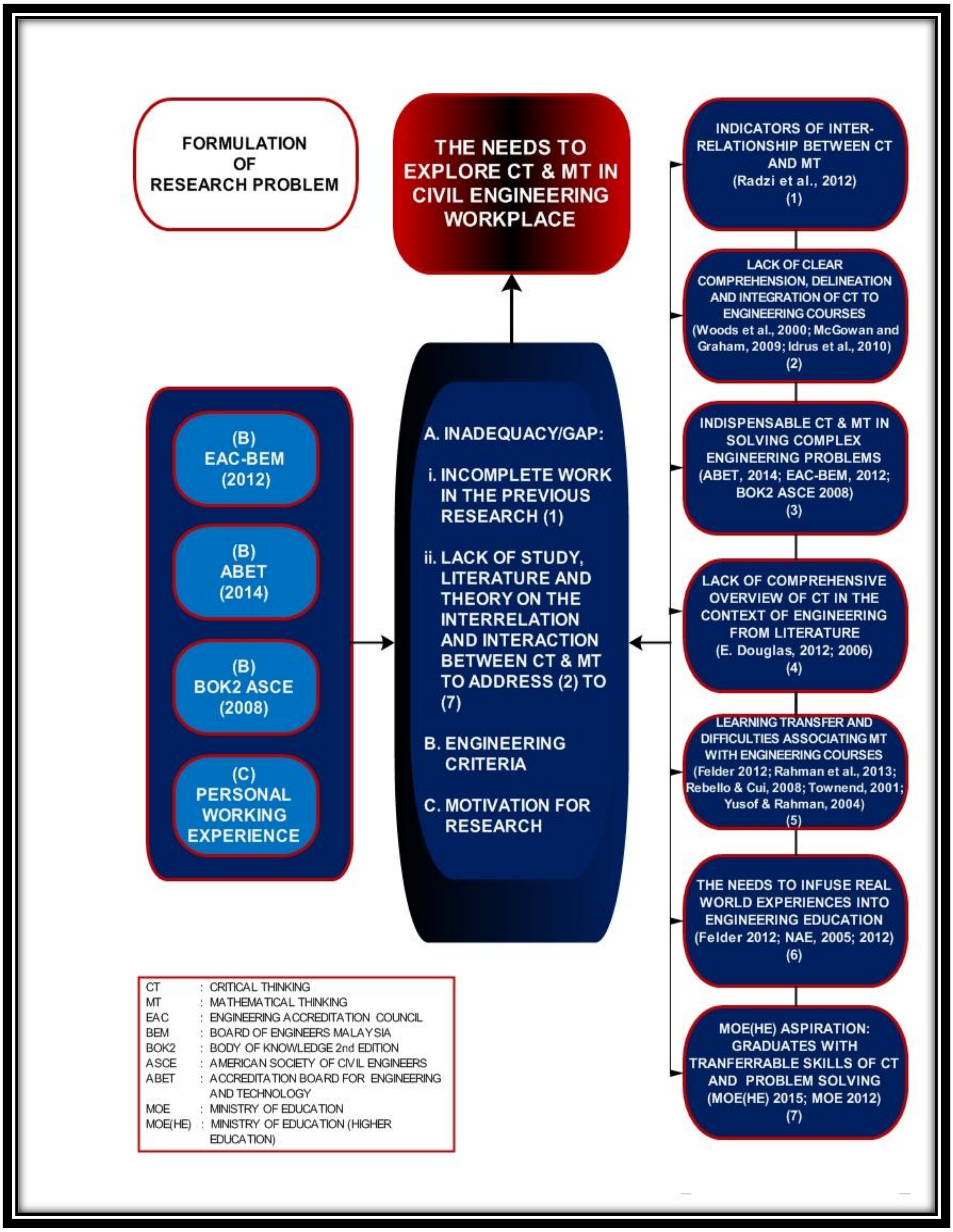


Figure 1.2: Formulation of Research Problem

1.3 Problem Statement

Engaging critical thinking and mathematical thinking in solving engineering problems is consistent with engineering criteria of the Engineering Accreditation Council, Board of Engineers Malaysia. Thus, it is timely and crucial to inculcate these two types of thinking into the current engineering education. However, information on the interrelation between both types of thinking in real-world engineering practice is found lacking in the extant literature, which is somewhat quite alarming to its perceived importance.

Similarly, findings from the previous research have shown congruence between critical thinking and mathematical thinking in solving engineering workplace problems. However, scarcely found in the extant literature, rigorous studies examining the interrelation and interaction between these two types of thinking in real-world engineering practice.

Also, hardly found any theory that gives insight into an engineering process which may relate critical thinking to mathematical thinking in real-world engineering practice.

The absence of this understanding among engineering education community has partially contributed to the ineffective attainment of critical thinking and mathematical thinking outcomes among engineering students. This unfortunate situation has been perpetuated through years and given rise to different conceptions, perceptions and emphasis on instructional approaches among mathematics and engineering educators.

Therefore, to achieve the critical thinking and mathematical thinking outcomes, a theory revealing insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice, need a first and foremost attention.

1.4 Research Goals and Objectives

This study sets a dual grand goal. The first goal is to develop a substantive theory pertaining to critical thinking and mathematical thinking. That is, to have an insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking used by engineers in real-world civil engineering practice. The second goal is to transform the theory into integrative diagrams as alternative models which can promote further understanding of the interaction among the pertinent elements and its implications for the engineering education. Congruent with the stated goals are the following research objectives:

1. To identify the pertinent elements of critical thinking and mathematical thinking used by practicing civil engineers in engineering design process

2. To establish the interrelation among the pertinent elements of critical thinking and mathematical thinking used in engineering design process

3. To explain the interaction among the pertinent elements of critical thinking and mathematical thinking used in engineering design process

1.5 Research Questions

In order to meet the objectives of this research, the following research questions steer the study:

1. What are the pertinent elements of critical thinking and mathematical thinking used by practicing civil engineers in engineering design process?

2. How do the pertinent elements of critical thinking and mathematical thinking used in engineering design process interrelate among each other?

3. How do the pertinent elements of critical thinking and mathematical thinking used in engineering design process interact?

1.6 Conceptual Framework

According to Miles, Huberman, and Saldaña (2014), a conceptual framework is simply a provisional version of the researcher's map of the area being investigated and evolves as the study progresses. It helps to decide what and how information should be collected and analyzed (Miles et al., 2014). In addition, it also guides the search for data and decreases the risk for unfocused data collection.

The conceptual framework for this study is shown in Figure 1.3. The framework incorporates two main components namely empirically driven analysis and concept-driven analysis. As this study adopts the modified grounded theory approach, the empirically driven analysis employs inductive approach during data analysis. Coding process in grounded theory analysis, particularly open coding, uses inductive approach, by which themes and categories emerge from the data through the researcher's careful examination, interpretation, and constant comparison.

On the other hand, the concept-driven analysis employs deductive approach for minding the scattering amplitude of the collected data to be reasonably confined and manageable. With respect to the Straussian grounded theory, relevant extant literature is used within a reasonable limitation as visualized in the framework and explained in the Section 2.6 and Chapter 3. Therefore, to be within the reasonable limitation, the deductive approach is employed through the lens of Facione for critical thinking (Facione et al., 2000; Facione, 1990, 2007, 2013) and Schoenfeld

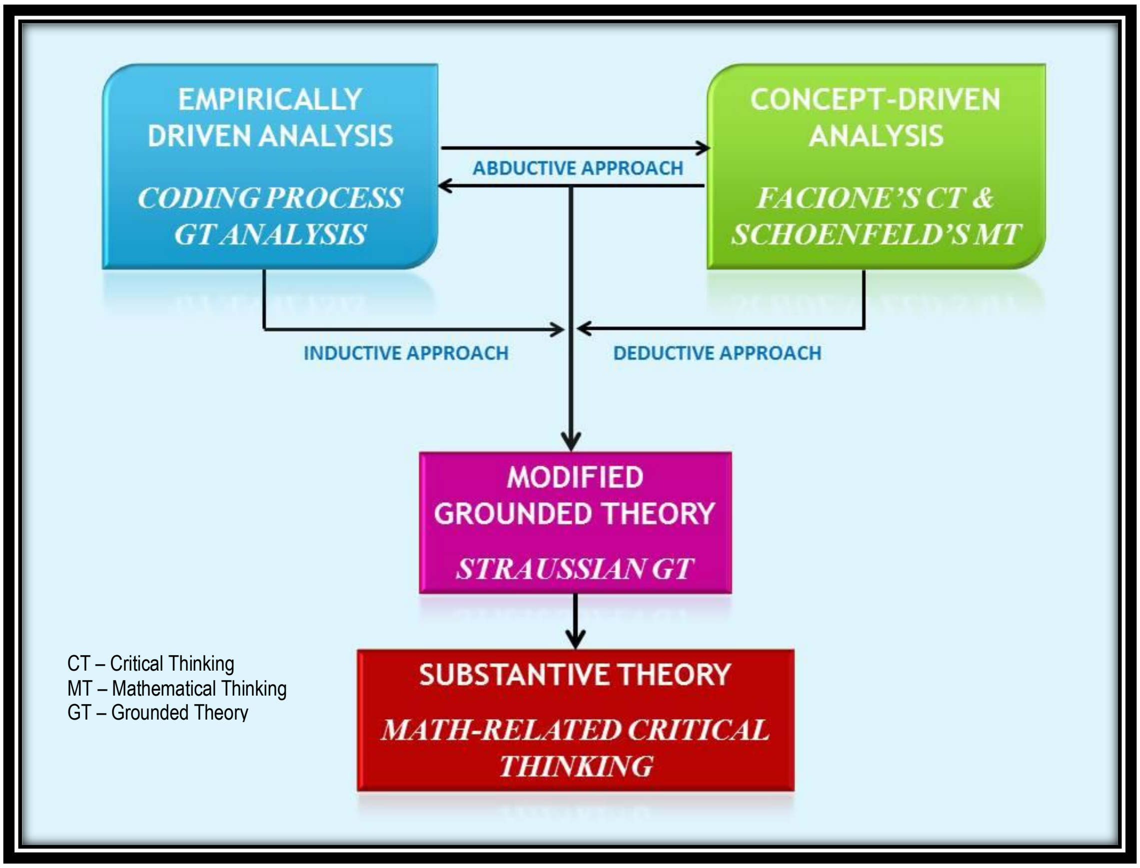


Figure 1.3: Conceptual Framework

for mathematical thinking (Schoenfeld, 1985, 1992). Nevertheless, the literature pertaining to the perspectives of Facione on critical thinking and Schoenfeld on mathematical thinking is not used as data per se. It is rather for examining data in-hand during the selection of pertinent elements, constant comparison process and in developing properties and dimensions for the Core Category as explained in Chapter 5.

It is an iterative process that involves abductive approach along the analysis process, in relation to the theoretical perspective of this study as explained in Section 3.2. In grounded theory analysis, the abductive approach is applied during the constant comparison and theoretical sampling in determining the saturation level. Categories emerged during open coding and pertaining extant literature are two main data sources used in this approach.

This study adopts the Straussian grounded theory approach after considering several aspects related to its suitability in answering the research questions as explained in Section 2.6. This modified grounded theory practices inductive, deductive and abductive approaches during data analysis for the grounded theory development. Ultimately, the method develops a substantive theory of Math-Related Critical Thinking.

1.7 Significance of the Study

This study develops a substantive theory pertaining to critical thinking and mathematical thinking. The theory can promote understanding of the interaction among pertinent elements of these two types of thinking, which is currently still lacking in relation to the civil engineering practice. This study is significant because no model or theory was found in the existing literature related to the interaction among pertinent elements of these two types of thinking. There is no empirical study has been done to have insights into the interaction between these two types of thinking in the real-world engineering practice.

Accordingly, scarcely found in the existing literature any educational research that uses a methodology for developing a theory in the context of engineering. This study introduces the use of qualitative research, particularly the modified grounded theory for developing a substantive theory in the context of engineering design process. This method adopts Strauss and Corbin’s version of grounded theory after considering several aspects related to the appropriateness of answering the research questions. The method is partly modified to fulfill the needs for answering the research questions but still preserving the basic rules of the methodology.

More importantly, understanding the interaction among pertinent elements of these two types of thinking is expected to contribute useful information to the engineering education, which is aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council. In the same way, in regards to the engineering design process in the real-world civil engineering practice, the emerging theory related to the critical thinking and mathematical thinking can be incorporated into the engineering curriculum and actively taught to the civil engineering students. It seems helpful to lubricate and accelerate the process of understanding, applying and transferring mathematical knowledge into the engineering education.

1.8 Scope and Delimitations

The area of study focuses on developing theory to reveal insights into the interaction among pertinent elements of critical thinking and mathematical thinking. The perspectives of Facione on critical thinking (Facione et al., 2000; Facione, 1990, 2007, 2013) and Schoenfeld on mathematical thinking (Schoenfeld, 1985, 1992) are used to confine and manage the pool of data during data analysis. This study emphasizes the interaction among the pertinent elements during engineering design process, in the real-world civil engineering practice context only. Informants for this study comprised of eight experts from two civil engineering consultancy firms, who have been involved in engineering design for at least five years.

Delimitations

1. This study was delimited to only informants from civil engineering consultancy firms, focusing on engineering design.

2. This study was also delimited to informant willingness to partake in the research study, candor, and capacity to recall and depict their experiences.

3. The unfamiliarity with terms such as critical thinking and mathematical thinking among informants since none of the informants were directly involved in the engineering education profession. Accordingly, this study was underpinned by the theoretical stance of interpretivism with symbolic interactionism and modified grounded theory as methodology. With that, the

researcher was positioned as social beings whose experiences, ideas and assumptions can contribute to the understanding and interpretation of social processes studied.

4. This study was contextualized to civil engineering practice. Therefore, is considered transferable to contexts of other engineering practice that having similar characteristics to the context under study, rather than generalizable.

1.9 Definition of Terms

The following terms are operationally defined for the purpose of this study.

Pertinent Elements

The selected major open codes or categories which were identified as the pertinent elements according to their predominant pattern and frequency of repetition, during open coding. The major open codes and categories were deduced from inductive codes. Prior to that, the inductive codes were classified as critical thinking or mathematical thinking, through the lens of Facione for critical thinking core skills and dispositions (Facione et al., 2000; Facione, 1990, 2007, 2013) and Schoenfeld for aspects of cognition of mathematical thinking (Schoenfeld, 1985, 1992).

Modified Grounded Theory

Initial grounded theory approach by Glaser and Strauss (1967) with adaptions in particular ways to suit the research question, situation, and informants for whom the research is being carried out (Bulawa, 2014; Morse et al., 2009). In this study, modified grounded theory uses the version of Strauss and Corbin (1990, 1998) that also known as a Straussian grounded theory. The Straussian grounded theory approach is chosen due to its more inclusive attitude to the extant literature and systematic approach to data analysis compared to the initial grounded theory version.

Inductive Approach

A data-driven strategy for generating categories emerged from data. Developing themes emergently based on patterns in the data (Daly, Mcgowan & Papalambros, 2013). Codes/categories/themes are emergently developed during open coding process of raw data.

Deductive Approach

It is a concept-driven strategy to base categories on previous knowledge, which is defined as determining a coding scheme prior to looking at the data (Daly et al., 2013). In this study, there are two main sources: categories emerged during open coding process from the previous interview transcript analysis and pertaining literature relating to critical thinking and mathematical thinking. This strategy is applied during data analysis process and throughout constant comparative method.

Abductive Approach

It is an analytic induction for generating new ideas from a combination of the fundamental approaches of inductive and deductive (Suddaby, 2006). It allows the researcher to modify or elaborate extant concepts when there is a need to do so, as to achieve a better fit and workability of generated theory (Thornberg, 2012). This approach is applied mostly in open coding during data analysis process and throughout constant comparative method.

Substantive Theory

A provisional and context-specific theory related to a phenomenon and is developed inductively from empirical data to reach an abstract level (Henn, Weinstein & Foard, 2006; Star, 1998). In this study, the modified ground theory approach develops a substantive theory, which is also known as an emerging theory or a process theory.

Civil Engineering Practice

In this study, the civil engineering practice referred to engineering design process, as experienced by practicing civil engineers in engineering consultation firms. Engineering design is fundamental and central to engineering (Daly et al., 2013).

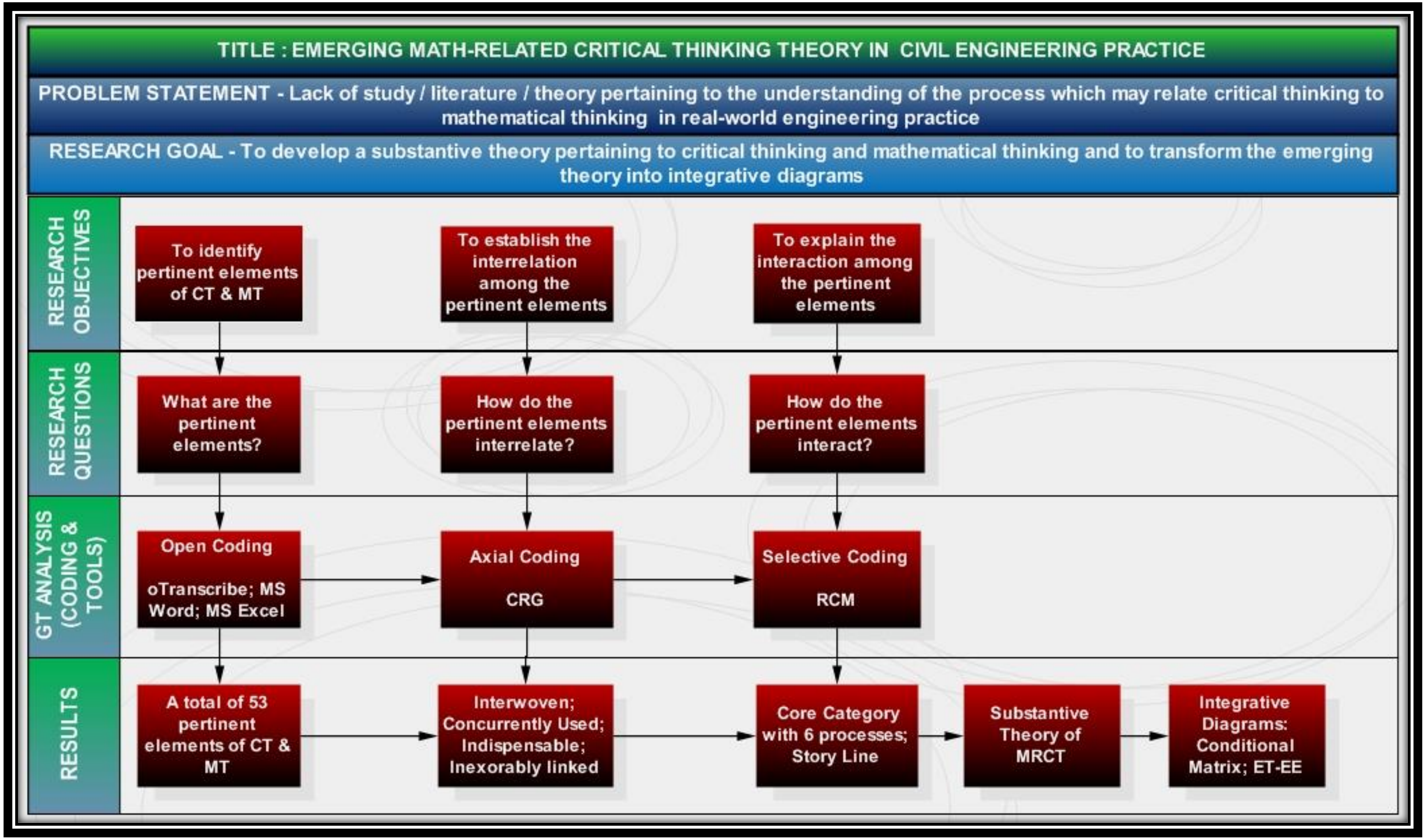
Engineering Design Process

Engineering design is a creative act with an expression of knowledge in improving or producing products or systems that meet human needs or to solve problems (Khandani, 2005). The engineering design process is a sequence of events and a set of guidelines that engineers follow to come up with a solution to a problem (Haik & Shahin, 2011). In this study, the process referred to civil engineering design activities in solving a civil engineering problem.

1.10 Overview of the Research Plan

This section provides an overview of the research plan as presented in Figure 1.4. It depicts the important aspects of the research work such as the problem statement, research goal, objectives and questions, research methodology and results. Grounded theory approach is used in this study. Three stages of analytic process involved in grounded theory analysis namely open coding, axial coding and selective coding, are shown in the diagram.

The diagram also highlights the analytic tools used in the grounded theory analysis according to the stages of analytic process. There are two main analytic tools used in this study namely Conditional Relationship Guide which is used during axial coding and Reflective Coding Matrix which is used during selective coding.



CT: Critical Thinking MT: Mathematical Thinking
GT: Grounded Theory CRG: Conditional Relationship Guide
RCM: Reflective Coding Matrix
MRCT: Math-Related Critical Thinking
ET-EE: Emerging Theory in Relation to Engineering Education

Figure 1.4: Overview of Research Plan

The emerging theory of this study is presented as a substantive theory of Math-Related Critical Thinking. The theory is then transformed into integrative diagrams. There are two main integrative diagrams generated from the substantive theory. One of the generated integrative diagrams is shown in the form of conditional matrix, as suggested by the Straussian grounded theory.

This overview helps the reader to have an initial broad-spectrum idea about the research work presented in this thesis.

1.11 Summary

This chapter introduced the study by presenting a brief orientation to the key features of this research. For that purpose, this chapter:

a) Discussed the background to the research and the research problem. Overview of the research background was depicted in Figure 1.2 for formulating the research problem. The formulated research problem was written in the statement of problem in Section 1.3.

b) Stated the detailed explanation on the research goals and objectives and the research questions of this study as presented in Section 1.4 and 1.5.

c) Introduced the conceptual framework of this research which clarifies a provisional approach of concepts and interrelationship among the concepts towards the research methodology used in this study. The conceptual framework was visualized in Section 1.6 of Figure 1.3.

d) Stated the significance of the study with the expected contributions to the body of knowledge, methodology and engineering education as covered in Section 1.7.

e) Described the research setting with its initial delimitation of scope and definition of several terms used in this study, in Section 1.8 and 1.9.

f) Briefly discussed an initial broad-spectrum idea about the research work to give an overview of the research to the reader. The overview of the research plan was visualized in Section 1.10 of Figure 1.4.

The following chapters provide expanded and detailed information of this study: Chapter 2 for Literature Review, Chapter 3 for Research Methodology, Chapter 4 for Data Acquisition, Chapter 5 for Data Analysis and Emerging Theory, and Chapter 6 for Discussion and Conclusion.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter aims to develop a better understanding of critical thinking and mathematical thinking by having an in-depth review on pertaining literature. It starts with a section of critical thinking by discussing its definitions, abilities, dispositions and characteristics conceptualization of a critical thinker, from perspectives of several proponents of critical thinking. It is then followed by a sub-section explaining a rationale for selecting perspective of Facione for critical thinking in this study. There are also sub-sections explaining about the necessity for civil engineers to have critical thinking and the need to teach critical thinking.

The next section is about mathematical thinking. It discusses definitions of mathematical thinking and a rationale for selecting perspective of Schoenfeld for mathematical thinking in this study. It is then followed by sub-sections explaining in detail aspects of cognition of mathematical thinking and the significance of mathematics to civil engineering.

This study adopts modified grounded theory approach and focuses on civil engineering practice, particularly in engineering design. Thus, the following sections discuss considerations for choosing civil engineering practice and engineering design as the focus area of this research.

A review on grounded theory is also included to understand about the roots and development of modified grounded theory. The discussion covers the evolution of grounded theory from the classical grounded theory to the contemporary grounded theory and a justification for choosing Strauss and Corbin's version of grounded theory for this study. Figure 2.1 depicts the organization of this chapter.

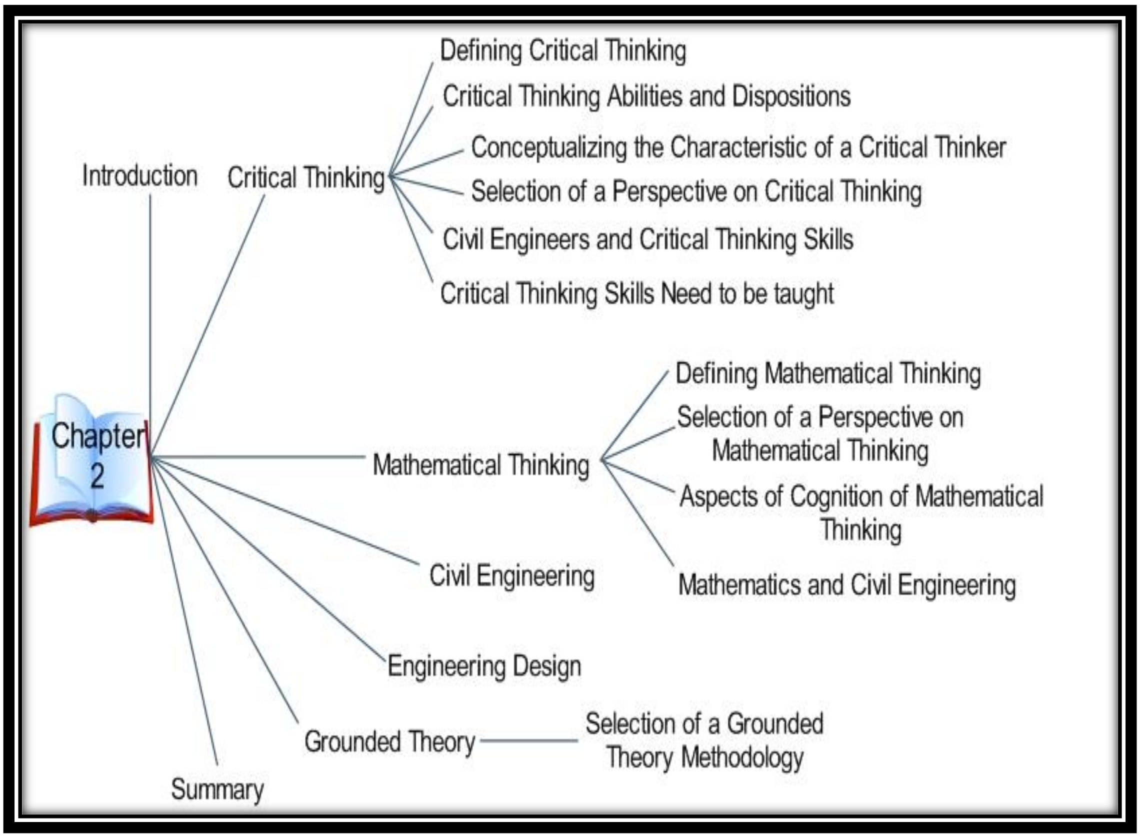


Figure 2.1: Thematic Structure of Chapter 2

2.2 Critical Thinking

Critical thinking has been one of the highly valued emphases of students' outcomes today, not only in academic settings of higher education but also in professional environments (Facione, 1990; Paul, 1995). It is called 'critical' not because it is negative or accusatory, but because it judges according to prescribed criteria (Beyer, 1990). Criteria are reasons, which having a high level of acceptance and respect in the community of inquiry (Lipman, 1988). For example, an architect judges a building by employing such criteria as utility, safety and beauty.

Educators worldwide argue that one of the key skills for surviving in an ever-changing world is the skill to think critically and as such, the foundation of an education system should be tailored to this imperative (Halpern, 2003; Paul, 1995). Paul argues that “critical thinking is the essential foundation for education because it is the essential foundation for adaptation to the everyday personal, social and professional demands of the 21st century and thereafter” (Paul, 1995, p.xi).

Consistently Halpern (2003) posits that this ability is arguably a necessity for the citizens of the 21st century to survive and thrive. President Anthony Carmona, Chancellor of the University of Trinidad and Tobago (UTT), made an appeal to Education Minister Dr Tim Gopeesingh to have critical thinking implemented in the school curriculum and offered to advanced level students (Banwarie, 2013). The Chancellor challenged the ministry to incorporate the critical thinking into the curriculum in believing that extensive knowledge does not make a man wiser but wisdom does. The researcher agrees with that belief because only a man who has wisdom is able to think and act wisely.

Ennis (1987) emphasized the ability to integrate facts and concepts acquired and later to be translated and effectively transferred in new situations. Thus, efforts in school could not be judged to have succeeded unless critical thinking instruction transfers to areas of practical concern. That is to say that students are not only to be taught to think critically in each subject, but also on how to transfer it to basic thinking tasks in life. Additionally, the initiation of the information age and the growing influence of the internet is another reason why educational systems in the world should incorporate critical thinking in their curriculum (Kadir, 2007).

2.2.1 Defining Critical Thinking

Definitions on critical thinking are produced according to different perspectives. However, there is still no universal consensus on a definition of critical thinking amongst educators, philosophers and psychologists in the field (Kadir, 2007). Thus despite the growing body of literature on critical thinking, consensus on a definition remains elusive. This lack of unity in defining critical thinking can be attributed to the differing perspectives from which disciplines such as philosophy and psychology view critical thinking (Kadir, 2007).

Facione (1990) defines critical thinking as purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or conceptual considerations upon which that judgment is based. Also, towards defining critical thinking, Facione (2007) argues that critical thinking is thinking that has a purpose (proving a point, interpreting what something means, solving a problem).

Complementary to this, the national panel of experts in the Delphi Project (Facione, 1990) are in consensus that a critical thinker must have a critical spirit which can be viewed as the propensity and inclination to think critically. Having a critical spirit does not mean that the person is always negative and hypercritical of everyone and everything (Facione, 2011). Critical spirit is collectively a cluster of dispositions, habits of mind, and character traits (Siegel, 2010).

In addition, Lipman (1988) argues that critical thinking is skillful, responsible, thinking that facilitates good judgment based on certain reasons such as; it relies upon criteria, it is self-correcting, and is sensitive to context. Since critical thinking is skilful thinking, that skill cannot be defined without criteria that evaluate the skill. Examples of criteria as mentioned by Lipman (1988) are validity, evidential warrant and consistency.

Critical thinking is defined as the ability to apply knowledge and intelligence in making decisions and giving opinions on issues (Knutson, 2012). In accordance with the statement, critical thinking is considered as a mode of thinking that improves the quality of thinking about any subjects, contents or problems, by skillfully analysing, accessing and reconstructing thoughts (Paul, 2007). Like-mindedly, making good judgment with desirable outcome is the product of thinking process, in agreement with having critical thinking which use those cognitive skills or strategies in increasing the probability of a desirable outcome (Halpern, 2003).

Paul (1990) considers critical thinking as disciplined, self-directed thinking which exemplifies the perfections of thinking appropriate to a particular mode or domain of thought which comes in two forms. It is to be sophistic or weak sense of critical thinking if it is disciplined to serve the interests of a particular individual or group, to the exclusion of other relevant persons and groups. Otherwise, if disciplined to take into account the interests of diverse persons or groups, it is fair-minded or strong sense critical thinking (Paul, 1990).

Two-component conception of critical thinking, encompasses both a reason-assessment component (abilities) and a critical-spirit component (dispositional), is endorsed by most theorists (Bailin & Siegel, 2003; Siegel, 2010). Ennis (1987) from the philosophical based theories views critical thinking as a practical reflective activity that has reasonable belief or action as its goal. There are five key ideas put forward here: practical, reflective, reasonable, belief, and action which combine into the following working definition: “Critical thinking is reflective and reasonable thinking that is focused on deciding what to believe or do” (Ennis, 1985). Then, the attributes of critical thinking are further elaborated into thirteen dispositions and twelve abilities. In addition, Ennis also prescribes taxonomy of critical dispositions and abilities. This taxonomy is not only delineating the skills that critical thinking involves, but also outlined dispositions that the critical thinker ought to possess (Ennis, 1985, 1987).

Unlike the philosophy-based theories, psychology-based theories are grounded in the cognitive dimension of critical thinking. For instance Sigel (1984) viewed it as an active process involving a number of denotable mental operations such as induction, deduction, reasoning, sequencing, classification and definition of relationships. Whereas Villalba (2011) considered critical thinking as a part of convergent thinking which involves the evaluation, analysis, synthesis, and interpretation of something to provide a judgment.

On the other hand, Bloom's Taxonomy which is a multi-tiered model, classifying thinking according to six cognitive levels of complexity and being hierarchical in nature. It views thinking as a set of skills that range from lower order to higher order. The higher order skills require more complex thinking than the lower ones which are seen as needing basic and less complex thinking. Lewis and Smith (1993), attempt an all-encompassing definition of higher order thinking which they conceive as the kind of thinking that *"occurs when a person takes new information and information stored in memory and interrelates and/or rearranges and extends this information to achieve a purpose or find possible answers in perplexing situations"*(p.136). This appears to be similar to what Bloom associates with his idea of synthesis (Krathwohl, 2002). That definition of higher order thinking also reflects mental activity and mental process, which are defined as cognition and cognitive process by Matlin (2009).

Definitions of critical thinking are indeed generalizable at the level of context and purpose (Kadir, 2007). However, critical thinking is not being restricted exclusively to a particular conception. Rather, building on consensus with regard to the essence of critical thinking that is emergent in the various fields. Therefore, critical thinking is seen like democracy, has myriad manifestations which are largely informed by its context and purpose (Kadir, 2007).

Consistent with the described conceptions, several popular definitions of critical thinking contain the following five common elements: identifying central issues and assumptions, making correct inferences from data, deducing conclusions from data provided, interpreting whether conclusions are warranted, and evaluating evidence or authority (Ennis, 1985; Furedy & Furedy, 1985). Other elements of critical thinking include: making a statement or argument supported with evidence (Beyer, 1995), recognizing important relationships (Ennis, 1985; Furedy & Furedy, 1985), defining a problem and forming relevant hypotheses (Ennis, 1985). While this touches only briefly on the concept of critical thinking, it seems that many of these elements could be likened to higher order levels of thinking, which attempt to explain “how” or “why”, as compared to lower order knowledge levels, which focus simply on “what” (Kadir, 2007; Villalba, 2011).

A summary of several definitions of critical thinking is given in the Table 2.1. This table provides a comprehensive meaning of critical thinking which helps the researcher in relating emerging theory to critical thinking as discussed in Section 6.2.2.1.

2.2.2 Critical Thinking Abilities and Dispositions

The lack of unity in defining critical thinking has somewhat contributed to the varied definitions of critical thinking abilities and dispositions amongst educators, philosophers and psychologists in the field. As has been much discussed in the above section of defining critical thinking, various definitions of critical thinking abilities and dispositions arose. It may be due to the differing perspectives, contexts, purposes, and influences of the philosophical and psychological conceptions of critical thinking itself.

The national panel of experts in the Delphi Project (Facione, 1990, 2007) eventually reached to a conclusion that critical thinking is encompassed in two dimensions, which are the cognitive skills dimension and the affective dimension. In parallel, Bailin et al. (1999) argue that if an attribute is required by persons in order to fulfill a standard of good thinking or if it will significantly increase the chances that their thinking will fulfill such standards, it can legitimately be regarded as an attribute that should be fostered in a critical thinker.

Table 2.1: Review Summary of Definitions of Critical Thinking

Num.	Proponents of Critical Thinking Skills	Definitions of Critical Thinking	Remarks
1	Facione et al. (2000); Facione (1990) APA Delphi Research Project	• Critical thinking as purposeful, self-regulatory judgment which results in interpretation, analysis, evaluation, and inference, as well as explanation of the evidential, conceptual, methodological, criteriological, or conceptual considerations upon which that judgment is based • Critical thinking is judging in a reflective way what to do or what to believe	Must have a critical spirit which can be viewed as inclination to think critically.
2	Ennis (1985, 1987, 1991) A Logical Basis for Measuring Critical Thinking Skills. *Educational Leadership*, *43*(2), 44–48	Critical thinking is reflective and reasonable thinking that is focused on deciding what to believe or do.	Five key ideas: practical, reflective, reasonable, belief and action. Critical thinking not equivalent to higher order thinking (HOT) skills, but includes most or all of practical HOT skills (refer to Bloom's taxonomy)
3	Paul (1990) What Every Person Needs to Survive in a Rapidly Changing World. Center for Critical Thinking and Moral Critique	Disciplined, self-directed thinking which exemplifies the perfections of thinking appropriate to a particular mode or domain of thought.	It comes in two forms: sophistic or weak-sense critical thinking and fair-minded or strong-sense critical thinking.

Table 2.1: Review Summary of Definitions of Critical Thinking - continue

Num.	Proponents of Critical Thinking Skills	Definitions of Critical Thinking	Remarks
4	Bailin, Case, Coombs, & Daniels (1999) Conceptualizing critical thinking. J. Curriculum Studies, Vol. 31, No. 3, 285-302	• Thinking that must be directed towards some end or purpose such as answering a question, making a decision, solving a problem, resolving an issue, devising a plan. • Thinking aimed at making a judgment.	Having at least three features: • Done for the purpose of making up one's mind about what to do or believe • To fulfill standards of adequacy and accuracy • To fulfill relevant standards to some threshold level
5	Lipman (1988) Critical Thinking -What Can It Be? Educational Leadership	Skillful, responsible thinking that facilitates good judgment because it relies upon criteria, is self-correcting and sensitive to context	Clear distinctions between ordinary thinking and critical thinking.
6	Paul and Elder (2008) The Miniature Guide to Critical Thinking Concepts and Tools	Critical thinking is the art of analyzing and evaluating thinking with a view to improving it; self-directed, self-disciplined, self-monitored, and self- corrective thinking	Requires rigorous standards of excellence and mindful command of their use; entails effective communication and problem solving abilities and a commitment to overcoming native egocentrism and sociocentrism.

As to the cognitive skills, the experts (Facione, 1990, 2007) include several skills as being at the very core of critical thinking, as tabulated in Table 2.2. This table serves useful information to help the researcher in classifying the emergent elements of critical thinking according to critical thinking core skills during open coding. To classify the emergent elements of critical thinking is a part of data analysis process in answering the research questions.

In the executive summary of the Delphi Report, Facione (1990) concludes that there is a growing consensus that a complete approach to developing college students into good critical thinkers must include the nurturing of the disposition toward critical thinking. Some might argue that cultivating the disposition is necessary before implanting the skills, but a developmental perspective would suggest that skills and dispositions are mutually reinforced and, hence, should be explicitly taught and modeled together (Facione, Giancarlo, Facione & Gainen, 1995). In either case, common sense tells that a strong overall disposition toward critical thinking is integral to insuring the use of critical thinking skills outside the narrow instructional setting (Facione et al., 1995).

For the purpose of instruction and developmental academic advising, findings from the California Critical Thinking Dispositions Inventory (CCTDI) reveal some significant implications. Strength in a given dispositional attribute indicates that a person is more inclined to use what skills he or she may have, while opposition to a given aspect of the overall disposition toward critical thinking suggests that a person would be inclined not to use his or her skills, even if they were considerable (Facione et al., 1995).

Table 2.2: Cognitive Skills of Critical Thinking (Facione, 1990, 2007)

Core Skills	Skills	Sub-skills
Interpretation	to comprehend and express the meaning or significance of a wide variety of experiences, situations, data, events, judgments, conventions, beliefs, rules, procedures, or criteria	categorization, decoding significance, and clarifying meaning
Analysis	to identify the intended and actual inferential relationships among statements, questions, concepts, descriptions, or other forms of representation intended to express belief, judgment, experiences, reasons, information, or opinions	examining ideas, detecting arguments, and analyzing arguments
Evaluation	to assess the credibility of statements or other representations which are accounts or descriptions of a person's perception, experience, situation, judgment, belief, or opinion; and to assess the logical strength of the actual or intended inferential relationships among statements, descriptions, questions or other forms of representation.	
Inference	to identify and secure elements needed to draw reasonable conclusions; to form conjectures and hypotheses; to consider relevant information and to educe the consequences flowing from data, statements, principles, evidence, judgments, beliefs, opinions, concepts, descriptions, questions, or other forms of representation	querying evidence, conjecturing alternatives, and drawing conclusions
Explanation	being able to present in a cogent and coherent way the results of one's reasoning: 1) to state and to justify that reasoning in terms of the evidential, conceptual, methodological, criteriological, and contextual considerations upon which one's results were based 2) to present one's reasoning in the form of cogent arguments	describing methods and results, justifying procedures, proposing and defending with good reasons one's causal and conceptual explanations of events or points of view, and presenting full and well-reasoned, arguments in the context of seeking the best understandings possible
Self-regulation	self-consciously to monitor one's cognitive activities, the elements used in those activities, and the results educed, particularly by applying skills in analysis, and evaluation to one's own inferential judgments with a view toward questioning, confirming, validating, or correcting either one's reasoning or one's results	self-examination and self-correction

Facione (2007), when posing the question about what kind of a person would be apt to use their critical thinking skills, summarizes the experts' consensus that people with critical spirit would be apt to use critical thinking skills. In what counts as dispositions towards critical thinking, the experts listed them down as follows (Facione, 2007):

i. Inquisitiveness with regard to a wide range of issues
ii. Concern to become and remain well-informed
iii. Alertness to opportunities to use critical thinking
iv. Trust in the processes of reasoned inquiry
v. Self-confidence in one's own abilities to reason
vi. Open-mindedness regarding divergent world views
vii. Flexibility in considering alternatives and opinions
viii. Understanding of the opinions of other people
ix. Fair-mindedness in appraising reasoning
x. Honesty in facing one's own biases, prejudices, stereotypes, or egocentric tendencies
xi. Prudence in suspending, making or altering judgments
xii. Willingness to reconsider and revise views where honest reflection suggests that change is warranted

Additionally the experts included the following dispositions when they go beyond approaches to life and living in general:

i. Clarity in stating the question or concern
ii. Orderliness in working with complexity
iii. Diligence in seeking relevant information
iv. Reasonableness in selecting and applying criteria
v. Care in focusing attention on the concern at hand
vi. Persistence though difficulties are encountered
vii. Precision to the degree permitted by the subject and the circumstances

While Ennis (1987) has broken down the process of reflectively and reasonably deciding what to believe or do into a set of critical thinking dispositions, three basic areas of critical thinking ability, and an area of strategic and tactical ability in employing critical thinking (Ennis, 1987). These abilities and dispositions are the fundamental elements (Ennis, 1991) in Table 2.3 and Table 2.4 respectively.

To some extent, Paul (1990) has gone beyond straight epistemic views to include dialectical features, such as taking into account in advance the objections or concerns of others. These features are not only needed for the pursuit of truth, but also for the sake of fairness and consideration of others-when one thinks critically in formulating and examining real arguments and decision in context (Ennis, 2008). Paul (1990) suggests the following seven interdependent intellectual traits of mind to be cultivated for students to become critical thinkers in the strong sense:

a. **Intellectual Humility**: Awareness of the limits of one's knowledge, including sensitivity to circumstances in which one's native egocentrism is likely to function self-deceptively; sensitivity to bias and prejudice in, and limitations of one's viewpoint.

b. **Intellectual Courage**: The willingness to face and assess fairly ideas, beliefs, or viewpoints to which we have not given a serious hearing, regardless of our strong negative reactions to them.

c. **Intellectual Empathy**: Recognizing the need to imaginatively put ones in the place of others to genuinely understand them.

d. **Intellectual Good Faith** (**Integrity**): Recognition of the need to be true to one's own thinking, to be consistent in the intellectual standards one applies, to hold one's self to the same rigorous standards of evidence and proof to which one holds one's antagonists.

Table 2.3: Critical Thinking Abilities (Ennis, 1991)

<table>
<tr><td rowspan="5">Clarification</td><td>to identify the focus: the issue, question or conclusion</td></tr>
<tr><td>to analyze arguments</td></tr>
<tr><td>to ask and answer questions of clarification and/or challenge</td></tr>
<tr><td>to define term, judge definitions, and deal with equivocation</td></tr>
<tr><td>to identify unstated assumptions</td></tr>
<tr><td rowspan="2">Decision</td><td>to judge the credibility of a source</td></tr>
<tr><td>to observe, and judge observation reports</td></tr>
<tr><td rowspan="3">Inference</td><td>to deduce and judge deductions</td></tr>
<tr><td>to induce and judge inductions:
a. to generalizations
b. to explanatory conclusions (including hypotheses)</td></tr>
<tr><td>to make and judge value judgments</td></tr>
<tr><td rowspan="2">Metacognitive – supposition and integration</td><td>to consider and reason from premises, reasons, assumptions, positions and other propositions with which one disagrees or about which one is in doubt-without letting the disagreement or doubt interfere with one’s thinking (“suppositional thinking”)</td></tr>
<tr><td>to integrate the other abilities and dispositions in making and defending a decision</td></tr>
<tr><td rowspan="4">Auxiliary</td><td>to proceed in an orderly manner appropriate to the situation, for example,
a. to follow problem solving steps
b. to monitor one’s own thinking
c. to employ a reasonable critical thinking checklist</td></tr>
<tr><td>to be sensitive to the feelings, level of knowledge, and degree of sophistication of others</td></tr>
<tr><td>to employ appropriate rhetorical strategies in discussion and presentation (orally and in writing)</td></tr>
<tr><td>to employ and react to ‘fallacy’ labels in an appropriate manner</td></tr>
</table>

Table 2.4: Critical Thinking Dispositions (Ennis, 1991)

to be clear about the intended meaning of what is said, written or otherwise communicated	to seek as much precision as the situation requires
to determine and maintain focus on the conclusion or question	to try to be reflectively aware of one's own basic beliefs
to take into account the total situation	to be open-minded; consider seriously other points of view than one's own
to seek and offer reasons	to withhold judgment when the evidence and reasons are insufficient
to try to be well informed	to take a position (and change a position) when the evidence and reasons are sufficient to do so
to look for alternatives	to use one's critical thinking abilities

e. **Intellectual Perseverance**: Willingness to pursue intellectual insights and truths despite difficulties, obstacles, and frustrations.

f. **Faith in Reason**: Confidence that in the long run one's own higher interests and those of humankind at large will be served best by giving the freest play to reason, by encouraging people to come to their own conclusions by developing their own rational faculties.

g. **Intellectual Sense of Justice**: Willingness to entertain all viewpoints sympathetically and to assess them with the same intellectual standards, without reference to one's own feelings or vested interests, or the feelings or vested interests of one's friends, community, or nation.

Table 2.5 summarizes classification of critical thinking dispositions as advocated by four critical thinking proponents namely Paul (1990), Bailin et al. (1999), Ennis (1987) and Facione (2007). A cross mark in the table indicates that the particular critical thinking disposition is mentioned by the proponent. The classification has shown a wide range of critical thinking dispositions. Ennis and Facione emphasize broader aspects of critical thinking dispositions compared to the other critical thinking proponents.

Table 2.5: Classification of Critical Thinking Dispositions

Num.	Classification for Critical Thinking Dispositions	Paul, 1990 CCTMC	Bailin et al., 1999 J.Curri Studies	Ennis, 1987 New York: WH Freeman	Facione 1990, 2000 Delphi Project
1	respect for reasons & truths; seek reasons; faith in reasons; trustful of reasons	X	X	X	X
2	respect for high quality product & performance; intellectual good-faith (integrity); respect for legitimate intellectual authority	X	X		
3	inquiring attitude; inquisitiveness; try to be well informed; habitually inquisitive; well informed		X	X	X
4	open-mindedness; consider others' point of view; willing to consider		X	X	X
5	independent mindedness		X		
6	respect for others; be sensitive to the feelings, level of knowledge and degree of sophistication of others; intellectual humility	X	X	X	
7	intellectual work ethics; use and mention credible resources		X	X	
8	seek clear statement of the question; clear about issues			X	X
9	take into account total situation; seek as much precision; persistent in seeking results			X	X
10	diligent in seeking relevant information; orderly in times of complexity; orderly in complex matters			X	X
11	keep in mind original concern; focused in inquiry			X	X
12	look for alternatives; flexible			X	X
13	withhold judgment when evidence insufficient; intellectual sense of justice; honest in facing personal bias; fair-mindedness in evaluation	X	X	X	X
14	take positions when evidence & reasons are sufficient; prudent in making judgment; acquire good judgment		X	X	X
15	reasonable in selection of criteria; try to remain relevant			X	X
16	intellectual courage	X			
17	intellectual perseverance	X			

Table 2.6 summarizes classification of critical thinking abilities and dispositions as advocated by four proponents of critical thinking namely Paul (1990), Bailin et al. (1999), Ennis (1987) and Facione (2007). This table helps the researcher to take a broader view of critical thinking from different perspectives. Table 2.5 and Table 2.6 also provide useful information to the researcher in selecting the most appropriate perspective of critical thinking to be applied in this study as explained in Section 2.2.4.

2.2.3 Conceptualizing the Characteristic of a Critical Thinker

Similar to the case of defining critical thinking and critical thinking abilities and dispositions, there is no universal consensus on a definition of a critical thinker amongst educators, philosophers and psychologists in the field. This lack of unity in defining a critical thinker may again be attributed to the differing perspectives from which disciplines view critical thinking.

For being a good thinker means having the right thinking dispositions (Tishman, Jay & Perkins, 1993). To classify good thinkers are not merely assessing their cognitive capabilities, strategies and skills, but their enduring tendencies to explore, to inquiry, to seek clarity, to take intellectual risks, to think critically and imaginatively, set good thinkers apart. Those tendencies are known as thinking dispositions that ongoing guiding intellectual behavior (Tishman et al., 1993).

Facione et al. (1995) express concern that it would be impossible to understand the teaching of critical thinking without an appreciation of the characterological profile of the kind of individual one was trying to nurture. Hence, the consensus extended beyond identifying a core set of cognitive skills and sub-skills to the articulation of a description of the ideal critical thinker.

Table 2.6: Review Summary of Critical Thinking Abilities and Dispositions

Num.	Proponents of Critical Thinking	Critical Thinking Abilities	Critical Thinking Dispositions	Remarks
1.	(Facione, 1990, 2007) APA Delphi Research Project	Interpretation; Analysis; Evaluation; Inference; Explanation; Self-regulation	Inquisitiveness; Well informed; Alertness to use CT; Trust of reasoned inquiry; Having self-confidence; Open mindedness; Flexibility in alternatives & opinions; Consider others opinions; Fair mindedness; Honesty regarding biases, egocentric; Prudence regarding judgments; Willingness in self-appraisal; Clarity; Orderliness; Diligence; Reasonable; Focus; Persistence; Precise	Outcomes of the consensus among the national panel of experts; distinguishes clearly between abilities and dispositions
2.	Ennis (1987, 1991) Taxonomy of Critical Thinking Dispositions and Abilities. Teaching Thinking Skills: Theory and Practice. New York: W. H. Freeman	Identify focus; Analyze arguments; Clarifying/Challenging; Define terms, judge definitions; Identify unstated assumptions; Judging credibility; Deductioning; Inductioning; Make & judge value judgments; Consider & reason; Integrate other abilities and dispositions; Orderly; Sensitivity.	Clear about intended meaning; Maintain focus; Consider total situation; Seek & offer reasons; Be well informed; Seek alternatives; Seek precision; Reflectively aware of one's belief; Open-minded; Not judgmental; Take position when sufficient evidence/reasons; Use one's CT abilities.	Consider familiarity with and knowledge of the area or topic in which thinking occurs are important. Approach issue with sufficient Sensitivity, Experience, Background Knowledge and Understanding of the situation, (Ennis, 2008)

Table 2.6: Review Summary of Critical Thinking Abilities and Dispositions - continue

Num.	Proponents of Critical Thinking	Critical Thinking Abilities	Critical Thinking Dispositions	Remarks
3.	Paul (1990), What Every Person Needs to Survive in a Rapidly Changing World. Center for Critical Thinking and Moral Critique	Macro-Abilities and Micro-Skills	***Traits of Mind***: Intellectual humility; Intellectual courage; Intellectual empathy; Intellectual good faith (integrity); Intellectual perseverance; Faith in reason; Intellectual sense of justice.	
4.	Bailin et al. (1999). Conceptualizing critical thinking. J. Curriculum Studies, Vol. 31, No. 3, 285-302		***Attitudes/Habits of Mind***: Respect for reasons and truth; Respect for high quality products/perfomances; Inquiring attitude; Open-minded; Fair-minded; Independent-minded; Respect for others; Respect for legitimate intellectual authority; Intellectual work ethic.	Characterize critical thinker in terms of intellectual resources: Background & Operational knowledge; Knowledge of key critical concepts; Heuristics; Habits of mind. There are certain standards when engaging in CT, must be aware & must strive to fulfill them

"The ideal critical thinker is habitually inquisitive, well-informed, trustful of reason, open minded, flexible, fair-minded in evaluation, honest in facing personal biases, prudent in making judgments, willing to reconsider, clear about issues, orderly in complex matters, diligent in seeking relevant information, reasonable in the selection of criteria, focused in inquiry, and persistent in seeking results which are as precise as the subject and the circumstances of inquiry permit. Thus, educating good critical thinkers means working toward this ideal. It combines developing critical thinking skills with nurturing those dispositions which consistently yield useful insights and which are the basis of a rational and democratic society." (Facione, 2007, p. 22).

Bailin et al. (1999) in their initiative to conceptualize a critical thinker suggest that the best way to characterize a critical thinker is in terms of intellectual resources which constitute of five kinds: background knowledge, operational knowledge, knowledge of key critical concepts, heuristics (strategies, procedures, etc.) and habits of mind. The depth of knowledge, understanding and experience persons have in a particular area of study or practice is a significant determinant of the degree to which they are capable of thinking critically in that area. However, having the intellectual resources necessary for critical thinking does not, by itself, make one a critical thinker. "One must also have certain commitments, attitudes or habits of mind that dispose him or her to use these resources to fulfil relevant standards and principles of good thinking" (Bailin et al. , 1999, p. 294).

Having mental agility and intelligence does not guarantee the ability to think critically. Ability to think clearly and rationally indicates that someone is having critical thinking. Moreover, when the person also able to engage in reflective and independent thinking. Someone with critical thinking is able to understand the logical connections between ideas, able to identify, construct and evaluate arguments, can detect inconsistencies and common mistakes in reasoning, solving problems systematically, do identify the relevance and importance of ideas, and also able to reflect on the justification of one's own beliefs and values (Lau, 2011).

2.2.4 Selection of a Perspective on Critical Thinking

In this study, besides focusing on the critical thinking skills, the dispositions of thinking are also being taken into account. It is important to understand a dispositional approach because an effective inculcation of thinking skills is by disposing a person to think creatively and critically in appropriate contexts (Tishman et al., 1993). The researcher has chosen to use Facione's perspective on critical thinking because it distinguishes clearly between abilities and dispositions. The abilities consist of six elements of cognitive skill such as interpretation, analysis, evaluation, inference, explanation and self-reflection. The dispositional dimensions include systematic (orderliness), inquisitiveness, judicious (maturity), truth seeking, confidence, open mindedness, and analyticity (Facione, 2013).

Another factor being considered in choosing Facione's perspective is its definition for critical thinking stands the outcomes of the consensus among the national panel of experts. A group of forty-six expert represented many different scholarly disciplines in the humanities, sciences, social sciences, and education, participated in a research project using Delphi Method, that lasted two years (Facione, 1990, 2013). As a result, outcomes from the consensus of the national expert represent a wide spectrum of meaning of abilities and dispositions of critical thinking. In view of that, the researcher has decided to choose Facione's perspective on critical thinking throughout this study.

2.2.5 Civil Engineers and Critical Thinking Skills

According to the Accreditation Board for Engineering and Technology (ABET): Engineering is the profession in which a knowledge of the mathematical and natural sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize economically the materials and forces of nature for the benefit of mankind (Jones, 2000).

This is in line with The American Society of Civil Engineers (BOK2 ASCE, 2008) which defines civil engineering as "…the profession in which a knowledge of the mathematical and physical sciences gained by study, experience, and practice is applied with judgment to develop ways to utilize, economically, the materials and forces of nature for the progressive well-being of humanity in creating, improving and protecting the environment, in providing facilities for community living, industry and transportation, and in providing structures for the use of humanity." It reflects the responsibility of civil engineers as a profession as well as the accountability entrusted by society in order to create a sustainable world and to upgrade the global quality of life.

Therefore, engineers need to have ability to think critically and provide the best optimum solutions in carrying out the challenging tasks. Moreover, engineering problems need to be evaluated analytically and critically, with the help of engineering and mathematical knowledge, for having wide spectrum of views considering all possible foresee consequences and making judgment. It is because the quality of thinking will portray the quality of the output, which is reflected in what are being designed, produced and built as engineers (Ceylan & Lee, 2003).

The importance of having critical thinking skills is indispensable in this rapidly changing world. Critical thinking is one of the most important attributes to be succeeded in the 21st century (Huitt, 1998). As mentioned by Paul (2007), "critical thinking transforms thinking in two directions ~ think more systematically and think more comprehensively as a result. And in thinking more comprehensively, means, thinking at a higher level, not because ones at a higher level as a person, but because ones are able to put thinking into the background and see it in a larger, more comprehensive framework."

Looking into deeper living contexts, in a world of accelerating change, intensifying complexity and increasing interdependence, ability to think critically is now also a requirement for economic and social survival (Hiler & Paul, 2005). A growing population in our developing country is demanding well maintained basic needs. It creates demand for civil engineers to deal with all sorts of complex engineering problems especially in the challenges of aging infrastructures such as maintaining water systems and waste treatment plants, managing projects to rebuild bridges, buildings, tunnels, repair roads and upgrade dams.

According to Bureau of Labor Statistics, United States Department of Labor, employment of civil engineers is expected to grow 19 percent from 2010 to 2020, which is about as fast as the average for all occupations (Civil Engineers, 2012). Despite the figure reflects that this profession is in high demand, it means nothing if it does not come together with its quality.

Since civil engineers are often confronted with complex problems, to be soundly solving the problems and expecting higher quality solutions, ability to think critically to provide effective solutions is absolutely indispensable (Ceylan & Lee, 2003). Think critically enables them to identify the most reasonable approach in dealing with the problems, able to reason inductively and deductively, as well as effectively and accurately assess the strengths and weaknesses of possible solutions, to form broad sound conclusions (Dorward, 2013).

2.2.6 Critical Thinking Skills Need to be Taught

Like playing a game, in order to be a good and skillful player, one has to learn about the game and keep practicing it. The same goes to critical thinking skills. Ability to think critically comes from learning and practices, and good thinking skills will not developed on their own as they must be taught (Beyer, 1984). Thus, critical thinking skills need to be taught and practiced.

Education system has served a good platform for acquiring knowledge. However, completing basic learning gives only superficial understanding of what being learned. Undeniable, knowledge and experience play a very important role in making good judgment, whereas, having critical thinking skills and critical thinking disposition gives quality critical thinking outcomes (Wood, 1993). Therefore, more focus need to be given in cultivating such thinking skills besides empowering content knowledge because ones must learn to think and reason critically to be knowledgeable and having intellectual curiosity (Wilkinson, 1988). Curriculum at school and higher learning institutions seems to be the most suitable means to execute the cultivation, because to becoming a critical thinker is a process and it improves with practice (Ceylan & Lee, 2003).

Universities offer engineering courses in many disciplines, hence, is timely for engineering educators to realize that effective engineering instruction cannot be based in memorization or technical calculation alone. In fact, it is essential to equip engineering students with critical thinking skills and dispositions in order to be able to effectively and professionally reasoning through the complex engineering issues and questions they will face as engineers (Paul, Niewoehner & Elder, 2006).

Critical thinking is not only the ability to think consistently but also the reflective act of questioning power/knowledge relations. Thus, critical thinking in and about engineering should include epistemic awareness and critical view, and brings meaning into the classroom by drawing together practices of reflection, reflexivity, and thinking critically within engineering (Claris & Riley, 2013). It also will bring about student questioning of course content, learning processes, and engineering in society, which showing positive response to outcomes-based education system.

Meaning, the curriculum must change its focus direction from only detail memorization of facts to more understanding and acquisition of basic principles and skills of a discipline. As well as providing students with ample opportunities for analytical, critical, constructive and creative thinking, and evidence-based decision making (EAC-BEM, 2012). To make it happen, some space in time and place has to be given to the engineering education in order to provide opportunities to put efforts in proper execution level. This is to avoid a scenario that when too many facts, too little conceptualizing, and when too much memorization, will be ending with too little thinking (Paul, 2004).

It is also mentioned by the engineering council about today's densely packed syllabuses can lead to a lack of clear understanding and difficulties among engineering students to create the necessary connections between mathematics and engineering applications, and to apply the techniques appropriately (Townend, 2001). Furthermore, developing critical thinking is the best preparation for life (Luan & Jiang, 2014). Therefore, the faculty, engineering educators, and curriculum should be ready for a revamp to be made, for a new path to be created, so that, essential skills such as critical thinking can be effectively inculcated through education.

In view of that, this study aims to provide useful information to engineering education about the use of critical thinking in real-world engineering practice. Engineering education should provide engineering students with ability to apply knowledge of mathematics and engineering and also analytical, critical and creative thinking skills to the solutions of engineering problems (BOK2 ASCE, 2008; EAC-BEM, 2012). Meanwhile, mathematics is regarded as a tool for cultivating thinking skills (Croft & Ward, 2001; Manoharan, Masnan & Abu, 2007). Instilling critical thinking in mathematics learning helps the students to learn and improve the skills how to think mathematically (Aizikovitsh & Amit, 2009, 2010; King et al., 2008).

Accordingly, to infuse real-world engineering experiences into engineering education is timely and crucial in enhancing students' thinking skills to be critical and analytical (Felder, 2012). Therefore, to have insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice becomes the goal of this study. The following section focuses on the discussion about mathematical thinking.

2.3 Mathematical Thinking

In the twenty-first century, people may benefit from being able to think mathematically because it is a valuable and powerful way of thinking about things in the world (Devlin, 2002). According to Schoenfeld (1992), learning to think mathematically means developing a mathematical point of view and developing competence with abstraction, symbolic representation, and symbolic manipulation. Mathematical thinking is important in a larger measure as it equips students with the ability to use mathematics (Stacey, 2007). This is not the same as doing mathematics which usually involves the application of formulas, procedures, and symbolic manipulation.

Devlin (2012) argues that mathematical thinking does not have to be about mathematics at all, but parts of mathematics provide the ideal target domain to learn how to think logically, analytically, quantitatively, and with precision. In addition, Schoenfeld (1992) also mentions that mathematical thinking is not merely involved mathematical content knowledge. The ability to think mathematically and to use mathematical thinking to solve problems is an important goal of schooling in such a way that mathematical thinking will support science, technology, economic life and development in an economy (Stacey, 2007).

2.3.1 Defining Mathematical Thinking

There are many different definitions and interpretations of the term mathematical thinking in literature based on experts view as well as scholars' definitions. Yet, there is no consensus on what mathematical thinking is (Sternberg, 2012). However, a lot of accordance in saying that the mathematical thinking is not a natural way of thinking; it needs to be taught and can be learnt (Devlin, 2012; Katagiri, 2004; Stacey, 2007).

Talking about the importance of teaching to cultivate mathematical thinking, Katagiri (2004) mentions that the method of thinking is the center of scholastic ability and mathematical thinking is the center of scholastic ability. Accordingly, mathematical thinking is regarded as the scholastic ability to think and make judgments independently, which is the most important ability to be cultivated in arithmetic and mathematics courses. Mathematical thinking is important as driving forces to pursue knowledge and skills, and for achieving independent thinking and the ability to learn independently (Katagiri, 2004).

Burton (1984) draws a clear distinction between mathematical thinking and the body of knowledge (i.e., content and techniques) described as mathematics. He emphasizes that the style of thinking labeled mathematical is applicable to content to which it is being applied and its application is general. It is called as ‘mathematical’ because the operations on which it relies are mathematical operations and not because it is thinking about mathematics (Burton, 1984).

Meanwhile, in education, mathematics is usually viewed through lenses of mathematical problem solving (e.g., Polya, 1957), mathematical modelling (e.g., Lesh & Lehrer, 2003), mathematical proofs (e.g., Harel, 2001, 2008) and mathematical thinking (e.g., Schoenfeld, 1992). One of the most prominent frameworks for mathematical thinking is the Schoenfeld’s perspective on five aspects of cognitions of mathematical thinking (Cardella, 2006).

Schoenfeld (1985, 1992) describes mathematical thinking as the ability to implement five aspects of cognition namely the knowledge base, problem solving strategies or heuristics, monitoring and control, beliefs and affects and practices.

Mason, Burton, and Stacey (2010) define mathematical thinking as a dynamic process, which increases the complexity of ideas ones can handle and consequently expand understanding. Stacey (2006) addresses that mathematical thinking is a process of highly complex activity and is important in three ways; mathematical thinking is an important goal of schooling, is important as a way of learning mathematics and for teaching mathematics.

Whereas Wood, Williams, and McNeal (2006) define mathematical thinking as the mental activity involved in the abstraction and generalization of mathematical ideas. This definition draws on the cognitive activities used when solving mathematical problems.

From the above review of mathematical thinking, to the researcher's best knowledge, thinking about mathematics cultivates mathematical thinking. When students use mathematics in solving mathematical problems, it is about thinking about mathematics. It involves a thinking process that nurtures students' thinking skill to think mathematically. Subsequently, when applying this thinking skill, for instance in solving engineering problems, the thinking process involves when adapting the thinking skill in solving engineering problems is the mathematical thinking. Therefore, thinking about mathematics during mathematics learning is a root and fundamental to promote the growth of mathematical thinking. Nevertheless, bear in mind that mathematical thinking is not thinking about mathematics.

With respect to this study, a fundamental way to cultivate mathematical thinking among engineering students is through mathematics learning because mathematical thinking is not a natural way of thinking but it needs to be taught and can be learnt (Devlin, 2012; Katagiri, 2004; Stacey, 2007).

2.3.2 Selection of a Perspective on Mathematical Thinking

The objective of the research is to understand the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in civil engineering practice. Interview transcripts are used as the main data source to identify the pertinent elements. The data are then being analysed epistemologically as grounding context for explorations into mathematical thinking. Schoenfeld's comprehensive explanation on the aspects of cognition of mathematical thinking has influenced the researcher to use Schoenfeld's perspective of mathematical thinking throughout this study.

Schoenfeld has come out with a framework for mathematical thinking in relation to mathematical problem solving (Schoenfeld, 1985). After having some reviews, an emerging consensus about the necessary scope of inquiries into mathematical thinking and problem solving has emerged (Schoenfeld, 1992). As a result, a framework of mathematical thinking in relation to problem solving, metacognition and sense-making in mathematics is developed. The framework tells what to look at during problem solving from the perspective of mathematical thinking. After spending about twenty five years doing research from 1985, Schoenfeld came out with his 'theory' of mathematical thinking in 'How We Think : A Theory of Human Decision-making, with a Focus on Teaching' (Schoenfeld, 2010). It explains how and why the problem solvers did what they did, such as applying particular knowledge or strategies, and on the decision they made in solving problems.

The framework of mathematical thinking established by Schoenfeld (1992) is used for identifying and understanding the mathematical thinking ones might engage (Cardella, 2006). The framework, in relation to problem solving, metacognition and sense-making in mathematics, tells what to look at during problem solving. Since one of the research objectives is to find out pertinent elements of mathematical thinking used by civil engineers in their practice, the framework is appropriate to be used to meet the objective of this study. The selection of this framework to be used in this study has also been approved by Professor Alan Schoenfeld through email conversations with the researcher (Appendix A).

Another factor being considered is the availability and the access of appropriate data (Reiter, Stewart & Bruce, 2011). To find out why and how people think in solving a problem, a think-aloud protocol on task orientation, with minimal intervention is preferred (Schoenfeld, 2010). The researcher appreciates the task out loud technique for collecting data. However, in this study, the informants are professional engineers and this technique is seemed impractical to be executed, considering the engineers' availability and nature of professionalism. Therefore, conducting interviews with the informants in collecting data in terms of experiences in executing their tasks is thought to be the most appropriate method to be applied in this study.

For the reasons mentioned above, the framework of mathematical thinking established by Schoenfeld is considered fit to the purpose of this study.

2.3.3 Aspects of Cognition of Mathematical Thinking

Schoenfeld identifies five aspects of mathematical thinking, which are also known as five aspects of cognition (Schoenfeld, 1992). These are shown in Table 2.7 and further explained as follows.

Table 2.7: Aspects of Cognition of Mathematical Thinking (Schoenfeld, 1992)

Aspects of Cognition	**Description**
Knowledge Base	Cognitive resources; Mathematical knowledge base
Problem Solving Strategies (Heuristics)	Strategies used in solving mathematical problems
Monitoring and Control	Managing thinking; Cognitive resource capacity and limitation
Beliefs and Affects	Beliefs and feelings toward mathematics impact mathematical orientation toward problems
Practices	Engagement in mathematical practices

The first aspect of cognition of mathematical thinking according to Schoenfeld is the knowledge base. It is about knowing what knowledge and resources a problem solver has potentially at his or her disposal (Schoenfeld, 2012). Aspects of knowledge base relevant for problem-solving performance in a domain include: informal and intuitive knowledge about the domain; facts, definitions, and the like; algorithmic procedures; routine procedures; relevant competencies; and knowledge about the rules of discourse in the domain (Schoenfeld, 1992). For the purpose of this study, the knowledge base which is reflected as cognitive resource is considered as part of elements of mathematical thinking.

Schoenfeld regards problem solving strategies as one of five aspects of cognition of mathematical thinking. "Problem solving" at its most general was defined as trying to achieve some outcome, when there was no known method (for the individual trying to achieve that outcome) to achieve it (Schoenfeld, 2013), which can be attributed in terms of struggling with ill-structured problems. He further remarks that students will not be able to solve these non-routine problems by simply recalling and applying similar solution patterns that known as problem schemata (Schoenfeld, 1992). Problem solving has also been associated with multiple meanings that range from "working rote exercises" to "doing mathematics as a professional" (Schoenfeld, 1992).

The investigation of heuristics, the general mathematical problem-solving strategies or rules of thumb for successful problem solving was first pioneered by George Pólya. Pólya's problem solving technique involves four steps: understand the problem; devise a plan by finding the connection between the data and the unknown; carry out the plan; and looking back by examining the solution obtained (Polya, 1957). Heuristic strategies can be described as rules of thumb for successful problem solving, or general suggestions that help an individual to understand a problem better or make progress towards a solution (Schoenfeld, 1992). According to Schoenfeld, exploiting analogies, introducing auxiliary elements in a problem or working auxiliary problems, working forward from the data, decomposing and recombining, exploiting related problems, drawing figures, varying the problems and working backwards can be included as heuristic strategies.

The third aspect of cognition of mathematical thinking according to Schoenfeld is monitoring and control. Besides cognitive resources that consist of the knowledge base that is stored in the long term memory, an additional cognitive resource to be considered is the working or short term memory. Working memory or short term memory is the space where “thinking gets done” (Schoenfeld, 1992). The most important aspect of working memory is its limited capacity. Therefore, the limitations in the working memory is being taken into account in monitoring and control processes (Schoenfeld, 1992). Mathematical performance does not only depend on what one knows but also on how one uses that knowledge, and how efficient it is used (Schoenfeld, 1992). This describes the behaviors of individuals in facing major decisions about what to do in a problem. Such behaviors of interest include making plans, selecting goals and sub-goals, monitoring and assessing solutions as they evolved, and revising or abandoning plans when appropriate (Schoenfeld, 1992).

Schoenfeld noted the importance of discussions related to merits of suggestions offered and decisions to be taken during the process of problem solving among problem solvers. Ineffective execution at the control level and poor decision making during the process of problem solving can contribute to one's failure to solve problems (Schoenfeld, 1992). On the individual basis, this can imply that a problem solver needs also to self-examine and self-introspect as ideas, solutions or results start evolving by self-questioning and self-correcting one's analysis and answers. Schoenfeld (1992) asks to think meta-cognitively by posting three questions while problem solving: 1) What (exactly) are you doing? (Can you describe it precisely?) 2) Why are you doing it? (How does it fit into the solution?) and 3) How does it help you? (What will you do with the outcome when you obtain it?).

Schoenfeld considers beliefs and affects as an aspect of cognition of mathematical thinking. Beliefs are to be interpreted as an individual's understandings and feelings that shape the ways the individual conceptualizes and engages in mathematical behavior (Schoenfeld, 1992). Schoenfeld discusses belief system in the context of the set of understandings about mathematics that establishes the psychological context within which individuals do mathematics. How people determine their orientation toward problems, the tools and techniques they think are relevant, and even their conscious access (or lack of access) to potentially related and useful material depend on their mathematical "world views" (Schoenfeld, 1992).

Research indicates that experts and novices perceive different things in mathematical problem statements and they are led by those perceptions to approach the problem differently (Schoenfeld, 1992). The kind of mathematical environments one creates depends on how one thinks of mathematics — and thus the kinds of mathematical understandings that one's students will develop (Schoenfeld, 1992). Beliefs are abstracted from one's experiences and from the culture in which one is embedded (Schoenfeld, 1992). Therefore, it gives impact to their engagement in mathematical thinking and leads to the consideration of mathematical practices.

Schoenfeld identifies practices as the fifth aspect of cognition of mathematical thinking. It is all about the engagement in mathematical practices. Schoenfeld (1992) focuses on the practical side of the issues of socialization, describing instructional attempts to foster mathematical thinking by creating microcosms of mathematical practice. He identifies some of the practices such as defending claims mathematically, coming to grips with uncertainty, making multiple conjectures/hypothesis, and mathematical sense-making. Schoenfeld focuses on the practices of fostering mathematical thinking in mathematics instruction, while in this study the researcher focuses on the real-world practices that civil engineers engage in. Experience gained from this study gives more complete understanding of the involvement of mathematical thinking in the real-world engineering practice.

2.3.4 Mathematics and Civil Engineering

Mathematics, which has long been acknowledged, is an instrument of acquiring knowledge and as a tool for explaining, reasoning and analyzing engineering systems and processes (Croft & Ward, 2001; Manoharan et al., 2007). Thus, it is important to regard mathematics as a tool for cultivating thinking skills and not only as absolute logical system. Mathematics learned in learning institutions is not going to be used for jobs as it is but to teach students the skill how to think, which is called mathematical thinking (Dudley, 1997).

The imperative significance of mathematics in civil engineering is also being firmly asserted by the Body of Knowledge for the American Society of Civil Engineering (BOK2 ASCE, 2008). It has explicitly stated mathematics as one of the four foundational legs supporting the future technical and professional practice education of civil engineers. In accordance, the professional engineer must acquire not only empirical but also abstract understanding of mathematics (Sazhin, 1998).

Therefore, it is important to have insights into the relation between the mathematical knowledge and in-depth understanding with the real engineering practical application. This is to find the right balance and to nurture the skills of essential mathematical thinking into the engineering education. This insight into the relation is seemed crucial as prospective engineers need to be explained on how and why knowledge of mathematics is essential for their future practical work (Sazhin, 1998).

Indeed, mathematics and engineering are inexorably linked as mathematics is a language to describe the civil engineering world (Sazhin, 1998; Wood, 2008). The symbiotic relationship between mathematics and civil engineering is well established that demands civil engineers to be sound, competent and reliable in mathematical and engineering manipulation, evaluations, interpretations and innovations (Radzi et al., 2012).

Therefore, it becomes important to equip the engineers with a fluency of mathematics, as an essential weapon in modern graduate engineer's armoury (Mustoe & Lawson, 2002). It is because to be succeed as an effective and quality engineer, ones must have substantial knowledge of mathematics (Moussavi, 1998). Thus, to infuse insights into mathematics and mathematical thinking used in real-world engineering practice into engineering education is indispensable in order to produce quality prospective engineers.

2.4 Civil Engineering

Engineers are hired, retained, and rewarded for their abilities and expertise to solve workplace problems. Abilities to apply, identify, design, and solve engineering problems are essential learning outcomes for any engineering program (ABET, 2014; EAC-BEM, 2012). It is important for the engineering education to understand the real-world engineering problem and problem solving in order to better prepare students for the workplace (Jonassen, Strobel & Lee, 2006). Therefore, this study is conducted to identify and understand the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking used by civil engineers in real-world engineering practice.

Engineering fields are characterized into four main branches: chemical engineering, civil engineering, electrical engineering, and mechanical engineering. In this study, the researcher specifically focuses on civil engineering as the domain of the study. Several criteria have been considered in choosing civil engineering as the focus area of this research.

Civil engineering is regarded as the oldest engineering field. Civil engineering has contributed in cultivating civilization by providing a higher standard of living with its designs, buildings and facilities invented. Since 2980 B.C., civil engineers have started building things when the famous and amazing Egyptian Pyramids were being built, to a more recent modern marvel of the Golden Gate Bridge, the longest single span bridge (4200 feet) in the world in 1937 (Department of Civil & Environmental Engineering, 2012).

Civil engineering has strong connection with and contributed to community service, development, and improvement. It designs, constructs and maintains society's infrastructure and major construction projects such as the highways, buildings, tunnel, bridges and water systems. Civil engineers must often manage very complex projects and are also considered as problem solvers; facing the challenges of pollution, traffic congestion, drinking water and energy needs, urban redevelopment, and community planning (Department of Civil & Environmental Engineering, 2012; Dorward, 2013).

Science and mathematics are close related to the civil engineering profession (BOK2 ASCE, 2008; Nelson, 2012). It is crucial for civil engineers to have abilities to think clearly and to express their ideas with clarity and logic in executing their engineering tasks. Application of science and mathematics as an attachment to their profession is deemed indispensable, especially in designing projects that solve real-world problems (Dorward, 2013).

Employment of civil engineers is expected to grow and increase faster than average for at least a decade since 2010 (Civil Engineers, 2012; Department of Civil & Environmental Engineering, 2012). It is due to the growing population that requires civil engineers to design and build more things, as well as to meet the needs to replace and/or fix infrastructure that already beyond its life span.

Since civil engineering has a wide scope of application, this study concentrates on civil engineering design for certain reasons as explained in the following section.

2.5 Engineering Design

Design is central to all branches of engineering and provide engineering students an opportunity to integrate and apply the content knowledge of mathematics, science and engineering courses (Cardella & Atman, 2007). Therefore, design is a prime context for considering how civil engineers use critical thinking and mathematical thinking in real-world engineering practice.

According to ABET, engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet the stated needs. Among the fundamental elements of the design process is the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. In addition, it is essential to include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impact (ABET, 2014; Haik & Shahin, 2011).

Solving a design problem is a process reliant and the solution is subjected to unforeseen complications and changes as it develops (Khandani, 2005). Therefore, engineering design is a systematic iterative process of converting resources and solving technical problems for the benefit to mankind.

Emphasized in the accreditation policies for engineering programs that ability to design as an outcome and measure of professional preparation (ABET, 2014; EAC-BEM, 2012). It makes statements on the future of engineering the need for engineering graduates to design for the betterment of the world (Duderstadt, 2008). A deep understanding of the complex dynamics of design processes, teams, contexts, and systems is needed to support successful strategies in design education and practice (Daly et al., 2013). This understanding requires research methodologies that can capture the nature of the design process from a diversity of aspects, i.e., cognitive, creative, social, organizational, and experiential (Daly et al., 2013). For that reason, a deep insight into the interrelation and interaction between critical thinking and mathematical thinking in civil engineering practice, particularly during the engineering design process, is considered crucial and required in preparing the future engineers.

The main informants for this study are engineers from civil engineering consultancy firms. The selection is based on reason that most civil engineers work for consulting companies which design projects and produce plans and specifications for building purpose or government agencies (Department of Civil & Environmental Engineering, 2012). Design is a form of problem solving that is open-ended and complex (Jonassen, 2000). Design is the main context for understanding how civil engineers engage in critical and mathematical thinking because it is a practice which liaise to and regarded as an integral to all branches of engineering (Cardella & Atman, 2007; Dorward, 2013). Moreover, through managing design problems and projects, engineers integrate and apply the content knowledge of mathematics, science and engineering.

The design process is a sequence of events and a set of guidelines that takes the designers from visualizing a product to realizing it in a systematic manner (Haik & Shahin, 2011). In other words, it is a phenomenon identified through systematic guided changes toward an expected result. There are five main steps used for solving design problems are: 1. Define the problem 2. Gather pertinent information 3. Generate multiple solutions 4. Analyze and select a solution 5. Test and implement the solution (Khandani, 2005) .

When solving a design problem, it is common to go back to a previous step at any point in the process. It is due to the unworkable solution chosen and need to redefine the problem, collecting more information or generating different solutions (Khandani, 2005). That continuous iterative process is visualized in Figure 2.2 below. The five main steps of this generic engineering design process are referred to in relating the emerging theory of this grounded theory study to the engineering design process, as discussed in Section 6.2.2.2.

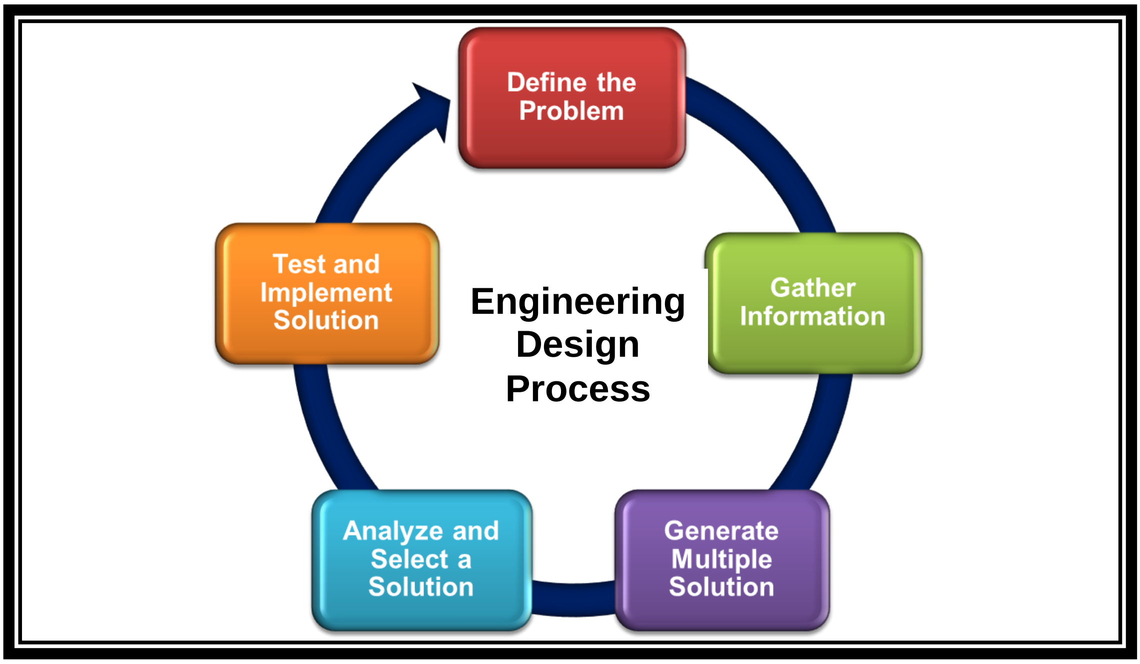


Figure 2.2: Engineering Design Process (Khandani, 2005)

2.6 Grounded Theory

Grounded theory is a specific methodology developed by Glaser and Strauss (1967) that researchers use for the purpose of building theory inductively from data (Corbin & Strauss, 2008). It is defined as a general methodology for developing theory that is grounded in data systematically gathered and analyzed (Strauss & Corbin, 1994).

Grounded theory was developed by Glaser and Strauss (1967) with the main thrust to generate theories regarding social phenomena by developing higher level understanding that is "grounded" in, or derived from, a systematic analysis of data (Lingard, Albert & Levinson, 2008). According to Creswell (2012), grounded theory research is a systematic, qualitative procedure used to generate a general explanation (grounded in the views of informants, called a grounded theory) that explains a process, action, or interaction among people.

In general, grounded theory should be used when little is known about a topic because the intent of any grounded theory study is to explore what's "out there" in the field and to generate a theory that is truly grounded in the data. Therefore, it is a methodological approach best suited for the inductive study of phenomena with little theoretical understanding (Corley, 2015). However, grounded theory studies can sometimes be employed when the knowledge about a particular topic is relatively advanced, too. The employment of grounded theory in these instances would be appropriate if previous research had identified particular variables or constructs, but with so little in the literature or no theory are generated that speculated on the relationship between those variables or constructs.

Similarly, Birks and Mills (2011) state that the unique nature of grounded theory methods' use is appropriate, when little is known about the area of study, when the generation of theory with explanatory power is a desired outcome, and when an inherent process is embedded in the research situation that is likely to be explicated by grounded theory methods.

In the context of this study, grounded theory is chosen based on the ontological and epistemological beliefs underpinning this research. Number of studies have been conducted on critical thinking (see, for example, Aizikovitsh & Amit, 2009, 2011; Douglas, 2006, 2012a; Jacquez, Gude, Hanson, Auzenne & Williamson, 2007; Luan & Jiang, 2014; Marcut, 2005; Norris, 2013) and mathematical thinking (see, for example, Burton, 1984; Cardella & Atman, 2007; Cardella, 2006; Kashefi, Ismail, Yusof & Rahman, 2012a, 2012b; Rahman et al., 2013; Yusof & Rahman, 2004). Unfortunately, there is no theory has been generated pertaining to the understanding of the process that relates mathematical thinking to critical thinking.

In view of that, grounded theory is an appropriate approach when the study of social interactions or experiences aims to explain a process, not to test or verify an existing theory (Lingard et al., 2008). It helps explore the processes and interactions that occur naturally in a phenomenon under study, and ultimately leads to the emergence of a theory (Strauss & Corbin, 1998).

Meanwhile, grounded theory is described by several particular fundamental characteristics such as: goal of theory development based on symbolic interactionism concepts, multistage process with cycles of data gathering and data analysis using abductive logic, and includes key components of theoretical sensitivity, constant comparison, theoretical sampling and theoretical saturation (Oktay, 2012). Chapter 3 further explains details of these characteristics of grounded theory.

In addition, a key aspect of grounded theory method is the development of categories and the relationships among the categories (Raduescu & Vessey, 2011). Therefore, grounded theory is chosen as the research methodology for this study, revealing insights into the interaction between these two types of thinking, as perceived by civil engineers in real-world engineering practice.

Qualitative research embraces many methodological approaches, including case study, phenomenology, ethnography, and grounded theory. A comparison is made to briefly explain a few basic differences between grounded theory and two other common qualitative research approaches, specifically phenomenology and ethnography (Aldiabat & Navenec, 2011; Goulding, 2005; Mello & Flint, 2009), as shown in Table 2.8. It visualizes how other distinct qualitative traditions compare to grounded theory in order to understand why and how to best use grounded theory approach in this study.

Table 2.8: A Comparison of Qualitative Research Approaches

	Grounded Theory	**Phenomenology**	**Ethnography**
Purpose	To understand social process; based on symbolic interactionism	To understand the essential meaning of lived experiences; as both philosophy and research approach	To identify, understand and explain cultures of people; based on anthropology
Data Collection	Interviews; observations; memos	In-depth interviews	Field work; voices of informants; observations; memos; pictures
Data Analysis	Open coding; Axial coding; Selective coding	Reading interview transcripts in full to gain sense of the whole phenomenon; identify patterns and differences across the transcripts by hermeneutic endeavour or intertextuality	Varied, may include content analysis & grounded theory; generate taxonomy to identify structures in the culture
Outcomes	Theory generation /development	Exhaustive description of meaning	Rich description of culture and patterns with emic and etic interpretations

Grounded theory practices inductive and deductive approaches during the constant comparative analysis, and is known as analytic induction or abduction, which is a product of mental activity and is important in grounded theory method (LaRossa, 2005; Suddaby, 2006). The logic of abduction allows the researcher to modify or elaborate extent concepts when there is a need to do so, as to achieve a better fit and workability of generated theory (Thornberg, 2012). Abduction reflects the process of creatively inferencing and verifying these inferences with more data by moving back and forth between data and theory iteratively (Timmermans & Tavory, 2012).

This iteration of grounded theory process relies on the perspectives of symbolic interactionism and pragmatism (Corbin & Strauss, 2008). In this study, the inductive and deductive approaches influence greatly data collection and analysis process, as shown in the conceptual framework in Figure 1.3.

Several versions of grounded theory method are available. The classical grounded theory, with its pure inductivism position, was developed by Glaser and Strauss in the mid of 1960s and published in The Discovery of Grounded Theory (1967). The version was ‘modified’ by Strauss and Corbin in Basic of Qualitative Research (1990, 1998) which introduced paradigm. Paradigm is an analytic tool devised to help analysts contextualize the phenomenon with process (Strauss & Corbin, 1998). Charmaz (2006) repositioned grounded theory as a flexible approach and not a strict methodology, with the constructivism stance.

Followed by the move made by Strauss and Corbin that redirected the method away from pure inductivism, Goldkuhl and Cronholm (2003, 2010) have introduced an alternative approach named Multi-Grounded Theory. Multi-Grounded Theory has acknowledged three different grounding processes, and gone beyond the pure inductivist by combining certain aspects from inductivism and deductivism, and added the explicit use of external theories.

A review of different approaches to grounded theory concerning coding procedures and theory development is presented in Table 2.9. The information in this table is extracted from Goldkuhl and Cronholm (2010), Heath and Cowley (2004) and Chen and Boore (2009).

Table 2.9 : Comparison of Different Approaches to Grounded Theory

Comparison Criteria	Glaser & Strauss (1)	Strauss & Corbin (2)	Charmaz (3)	Goldkuhl & Cronholm (4)	Remarks
Literature/Research interest reflection and revision	-	√	√	√	Restricted in (1), allowable in (2), (3) & (4)
Initial Coding	Substantive Coding	Open Coding	Initial Coding	Inductive Coding	Purely inductivism in (1), using analytical technique in (2), using line-by-line(in-vivo coding) in (3), include conceptual refinement process in (4)
Intermediate Phase	Continuous with previous phase	Axial Coding	Continuous with previous phase	Pattern Coding	Constant comparative method mainly in (1) & (3), paradigm model in (2) & (4)
Final Development	Theoretical Coding	Selective Coding	Focused Coding	Theory Condensation (three types of grounding process: theoretical matching, explicit empirical validation and evaluation of theoretical cohesion)	Selection of a core category in (1), (2) & (3), no single core category in (4)
Theory	Parsimony, modifiability	Detailed and dense process fully described	Acknowledgment of the social construction of the interview and participant observation	Multi-grounded ; data and theory based construction	(2) initiated modification of purely inductivism grounded theory while (4) transformed the grounded theory method beyond the inductivism stance.

2.6.1 Selection of a Grounded Theory Methodology

The three main grounded theory approaches are classic (Glaserian), Straussian and constructivist (Charmaz). In this study, modified grounded theory is referring to approaches of grounded theory other than Glaserian classical grounded theory. Inspired by the evolution of grounded theory and the appropriateness of answering the research questions in a reasonable confinement, modified grounded theory is chosen as a considerable approach in this study.

Modified grounded theory is considered a highly flexible and adaptable research methodology (Barnett, 2010). Every time grounded theory is used, it needs adaption in particular ways to suit the research question, situation, and informants for whom the research is being carried out (Bulawa, 2014; Morse et al., 2009). There is no one way of undertaking grounded theory studies as the initial approach by Glaser and Strauss was never intended to be dogmatic and yet not to renege from the pure inductive way of analyzing data (Bulawa, 2014; Goldkuhl & Cronholm, 2010).

In the ongoing evolution of grounded theory, the criteria for the use of extant theory should expand rather than restrict analytic possibilities (Seaman, 2008). The inclusive attitude to the existing knowledge, especially in data analysis and theory generation during systematic comparison (Strauss & Corbin, 1998), was a consideration in selecting the methodology. The classic approach avoids a pre-study literature review to minimize preconceptions and emphasizes the constant comparative method. Whereas the Straussian and constructivist approaches focus more on the beneficial aspects of an initial literature review and researcher reflexivity (Yarwood-Ross & Jack, 2015).

Moreover, researchers often build new knowledge on existing knowledge for cumulative theory development (Goldkuhl & Cronholm, 2010) and manipulate the existing knowledge and pertaining literature to understand and view further (Thornberg, 2012). For that, ignoring existing knowledge tends to be at the risk of reinventing the wheel, missing well-known aspects and repeating others' mistakes

(Goldkuhl & Cronholm, 2010; Thornberg, 2012). Therefore, knowing and using the existing knowledge is not for forcing the research into preconceived categories but as a flexible way to multiple possible lenses (Flick, 2014).

Furthermore, in the context of this study, the existing knowledge is also used for minding the abundance and scattering amplitude of the collected data to be reasonably confined and manageable. Several researchers, who used grounded theory approach in their studies have used and argued for more influence of prior theories in data analysis and theory generation, for example, see Bruce (2007); Kelle (2005); and Seaman (2008). Therefore, the researcher thought that the versions of grounded theory of Strauss and Corbin (1990, 1998) and adaptation of multi-grounded theory approach (Cronholm, 2004, 2005; Goldkuhl & Cronholm, 2003, 2010) would be well fitted to be incorporated into this research due to its more inclusive attitude to existing data and systematic approach to data analysis.

The method of analysis chosen for this study is a hybrid approach of grounded theory analysis that incorporated both the data-driven inductive approach of Strauss and Corbin (1990, 1998) and the deductive approach of multi-grounded theory by Goldkuhl and Cronholm (2003, 2010). The deductive part is drawn from the perspectives of Facione for critical thinking and Schoenfeld for mathematical thinking. Even though this study uses a qualitative method, the hybrid approach of grounded theory analysis is deemed necessary because there is still a need to have theoretical expectations that guide collection and analysis stage (Bruce, 2007).

Furthermore, researchers should have a critical stance towards information and always try to go beyond what has been said by different informants or find alternative information sources that can confirm the data (Goldkuhl & Cronholm, 2003, 2010). The hybrid approah is necessary if a researcher wants to use an inductive approach when the existing theories or prior research are used as a guide for articulation of meaningful themes (Boyatzis, 1998). This approach complemented the research questions by allowing the extant literature to guide the search for data while allowing for themes to emerge direct from the data using inductive coding.

Strauss and Corbin's version (1990, 1998) asserted that grounded theory is an action/interactional method of theory building, and that, an action-oriented paradigm model should be used. This version also has a structured pragmatic approach and allows analytic tools or techniques to be used during data analysis process. Either by using a variety of techniques, matrices or computers, it indicates that researchers need ways of probing into and organizing data (Strauss & Corbin, 1998).

In accordance with their assertion, this study uses research tools as data-oriented conceptual clarification to support grounded theory analysis and interpretation by linking categories more clearly to the data, namely, the Conditional Relationship Guide (CGR) and the Reflective Coding Matrix (RMC).

The Conditional Relationship Guide contextualizes the central phenomenon and relates categories linking structure with process (Scott & Howell, 2008; Scott, 2004). The Reflective Coding Matrix captures the higher level of abstraction necessary to bridge to the final phase of grounded theory analysis, selective coding and interpretation, and, ultimately to the theory developed or generated (Scott & Howell, 2008; Scott, 2004). The theory is a set of concepts that are related to one another in a cohesive whole, expressed as a substantive theory, which is contextual and never completely final (Sbaraini, Carter, Evans & Blinkhorn, 2011).

Another reason for not using the Glaser’s approach was that the researcher could not credibly maintain a naive stance because has conducted a preliminary literature review. Nevertheless, the knowledge from literature, mainly the constant comparative method (Glaser & Strauss, 1967; Glaser, 2008) is adopted in this study, in view of constructing theoretical comparison when making systematic comparison (Strauss & Corbin, 1990, 1998).

2.7 Summary

This chapter thoroughly described reviews of pertinent literature regarding critical thinking, mathematical thinking, related aspects of civil engineering and grounded theory. It focused on five main sections:

a) Section 2.2 explained an in-depth review of critical thinking by discussing its definitions from several perspectives of critical thinking proponents. It is then followed by discussions regarding abilities and dispositions of critical thinking and also characteristics of a critical thinker from different angles of view. It highlighted classification of complete summarizations of critical thinking as advocated by four critical thinking proponents namely Paul, (1990), Bailin et. al., (1999), Ennis, (1987) and, Facione (2007). The main focus was given on the perspective of Facione for critical thinking supported with some viewpoints justifying the selection. This section also briefly discussed the necessity for civil engineers to have critical thinking, besides engineering and mathematical knowledge, in dealing with engineering problems according to EAC-BEM, ABET and ASCE definitions and criteria of engineering and civil engineering. Before shifting to another section, a discussion about the needs to teach critical thinking skills to engineering students was discussed. The discussion was summed up with a view: engineering education should be ready for a revamp to be made and for a new path to be created, so that, essential skills such as critical thinking can be effectively inculcated through education in order to showing positive response to outcomes-based engineering education system.

b) Section 2.3 presented a detailed literature review of mathematical thinking by discussing what mathematical thinking is all about from different perspectives of mathematical thinking proponents. A selection of perspective on mathematical thinking was made for this study and for that, the perspective of Schoenfeld for mathematical thinking was chosen. A justification for the selection was discussed based on the specific requirements of the research, such as the need for having a comprehensive explanation of mathematical thinking framework that suits the study and the availability and the access of appropriate data. This section was continued with detailed explanation about five aspects of cognition of mathematical thinking by providing a discussion of each of the five aspects: knowledge base, problem solving strategies or heuristics, monitoring and control, beliefs and affects, and practices. At the end of this section, a discussion was made about the imperative significance of mathematics in civil engineering. A summarization was made by stating this statement: to infuse insights into mathematics and mathematical thinking used in real-world engineering practice into engineering education is indispensable in order to produce quality prospective engineers.

c) Section 2.4 and 2.5 discussed civil engineering and engineering design as the focus area of this research. The discussion underlined the criteria and considerations in choosing civil engineering and engineering design as the domain of this study, such as the privilege of civil engineering as the oldest engineering field, strong connection of civil engineering with society, the indispensability of applying science and mathematics as an attachment to civil engineering profession, and the centrality of design to all branches of engineering that provides opportunity to integrate and apply the content knowledge of mathematics, science and engineering courses. It was concluded that engineering design is a prime context for considering the use of critical thinking and mathematical thinking in real-world engineering practice.

d) Section 2.6 presented a review about grounded theory by explaining its background from classical to contemporary grounded theory. The review pointed out that as a research methodological approach, grounded theory helps exploring the natural processes and interactions in a phenomenon under study, and ultimately leads to the emergence of a substantive theory. That point suits well this study to explore the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice. A comparison was made between grounded theory and other common qualitative research approaches, specifically phenomenology and ethnography, to visualize how other distinct qualitative traditions compare to grounded theory in order to understand why grounded theory is used in this study. This section also presented a review of different approaches to grounded theory concerning coding procedures and theory development. The review mentioned that the modified grounded theory approach used in this study was chosen based on the ontological and epistemological beliefs underpinning this research. Also, due to the inclusion of existing experience and knowledge especially in data analysis and theory development during systematic comparison.

The next chapter defines the research methodology in which the modified grounded theory approach is adopted for this research, presenting the research design and discussing several methodological aspects.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The previous chapters clearly explained the reasons for conducting this research from several viewpoints. This chapter discusses the selected methodology that generates an appropriate research design to effectively address the research problem.

This chapter begins with a discussion on research philosophy which addresses the ontological and epistemological issues that has influenced the choice of research methodology. The philosophies underpinning this study guide the way through the methodological stance, to outline the particular methods used in this study. Then, the research process is described in full in the following sections such as operational framework, phases of research, informant selection criteria, data acquisition and data analysis. Figure 3.1 visualizes the organization of this chapter.

As far as methodology is concerned, this study adopts qualitative research method with modified grounded theory approach. A review about the method and justification of the method selection, have been discussed in detail in Section 2.6. Qualitative research is an exploratory study that provides flexibility and freedom to channel natural curiosity in exploring the phenomena under study (Corbin & Strauss, 2008). It studies phenomena in their natural settings, attempting to make sense of, or interpret based on the experience or meaning perceived by the informants (Denzin & Lincoln, 1994).

Strauss and Corbin (1994) mentioned that doing qualitative analysis is to make interpretations and must be based on multiple perspectives. Meanwhile, grounded theories connect those multiplicity of perspective with patterns and processes of action and interactions that eventually are linked with scrutinized conceptualization (Strauss & Corbin, 1994). Knowledge and meaningful reality are constructed through interaction between humans and their world, and are developed and conveyed into a social context (Crotty, 1998). Therefore, the social world can only be understood from the standpoint of individuals who are taking part in it (Cohen, Manion & Morrison, 2007). In particular, interpretivism aims to bring into consciousness hidden social forces and structures (Scotland, 2012).

Hence, it is appropriate to adopt qualitative-interpretivist approach in this research, as it is the suitable way for representing the multiple perspectives and experiences of the civil engineering world.

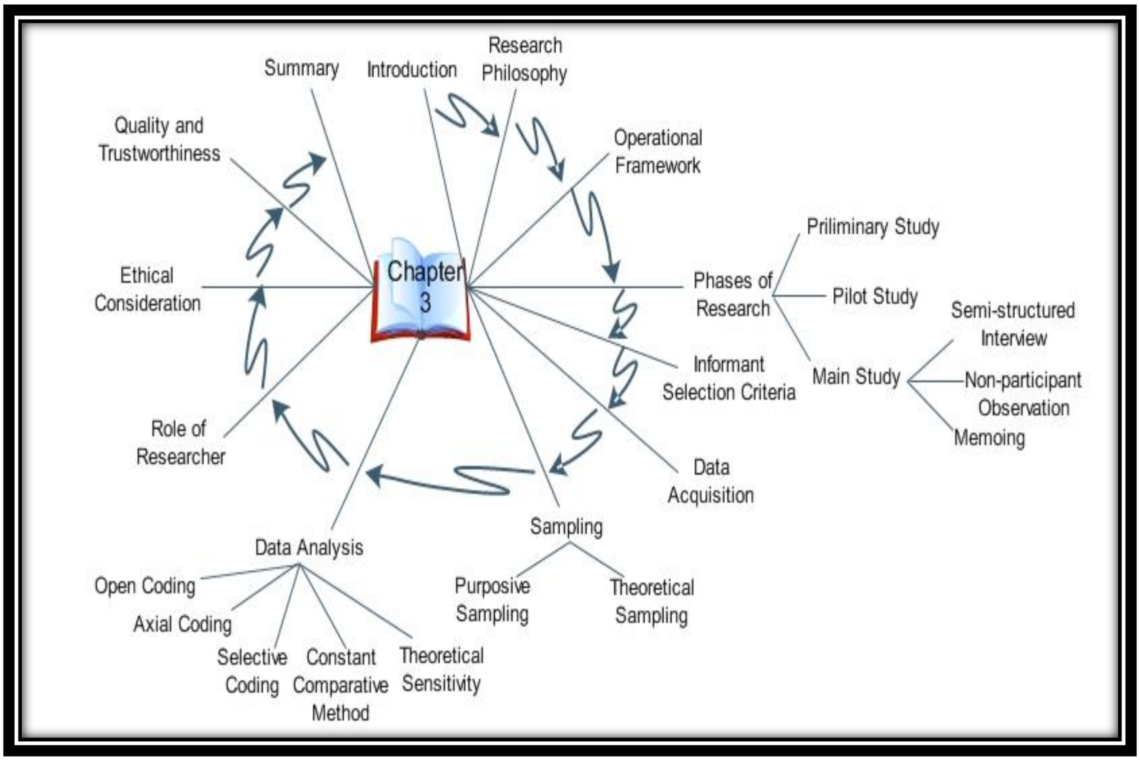


Figure 3.1: Thematic Structure of Chapter 3

3.2 Research Philosophy

In designing a rigorous research, it is very important to fully understand the philosophical and methodological position, and the methods to be employed, to achieve the research goals (Birks & Mills, 2011). A paradigm says about ontology, epistemology and methodology underpinning the research. It is essentially a worldview within which a researcher work, and a whole framework of belief, values and methods within research takes place (Guba & Lincoln, 1994). Moreover, the research philosophy contains important assumptions about the way in which a researcher views the world and underpinning the research strategy and the chosen method as part of the research strategy (Saunders, Lewis & Thornhill, 2009).

An understanding, appreciation and application of multiple paradigms to research are deemed most appropriate in order to have holistic and comprehensive understanding of social phenomenon (Bhattacherjee, 2012). In the same context, theoretical paradigms underlying this study are investigated, interpreted and analyzed under the light of two philosophies, namely interpretive/symbolic interactionism and pragmatism. This philosophical inclination embedded more significantly and seminal in Strauss and Corbin's version of grounded theory (Kenny & Fourie, 2014).

The relationship between the interpretive tradition of symbolic interactionism and grounded theory (Glaser & Strauss, 1967; Glaser, 1978) is strong and historical (Aldiabat, 2011; Handberg, Thorne, Midtgaard, Nielsen & Lomborg, 2014). Interpretive/symbolic interactionism (Blumer, 1969) sees the truth is contextual, depending (interpretation) on the situation, people being observed and even the person doing the observation and how the meaning is socially constructed but interpreted by the individual (Chism, Douglas & Hilson, 2008). The focus of this perspective is on the interactions between people and the world, based on the meaning given to the world by that individual.

Grounded theory and symbolic interactionism are compatible in their goals and assumptions which is can be classified as ontological, epistemological and methodological (Aldiabat, 2011). Similarly, Corbin and Strauss' 16 assumptions of grounded theory (Corbin & Strauss, 2008) provide key symbolic interactionist themes and their links to essential grounded theory methods (Chamberlain-Salaun, Mills & Usher, 2013). Ontological assumptions is about the nature of reality and what human beings can know about it (Guba & Lincoln, 1994).

For research that uses symbolic interactionism and grounded theory, the realities are considered to exist for human beings in a world of shared symbolic meanings (Aldiabat, 2011). For epistemological assumptions, it refers to the nature of the relationship between the knower and what can be known (Guba & Lincoln, 1994). In symbolic interactionism and grounded theory, the researcher and informants are assumed to be interactively linked in a mutual relationship in the natural field to investigate their behavior (Aldiabat, 2011).

Whilst, methodological assumptions refer to how the researcher can go about discovering the social experience, how it is created, and how it gives meaning to human life (Guba & Lincoln, 1994). For symbolic interactionism and grounded theory, human beings and shared meanings of reality can be defined only through interaction between and among the researcher and informants in the context of the phenomena of interest (Aldiabat, 2011).

In the context of this study, the interaction between mathematical thinking and critical thinking is explored based on the interpretation of the informants' perspectives and voices, concerning their experiences in real-world civil engineering practice contexts and also from non-participant observations. It is demonstrated through the inductive approach of empirical-driven analysis in the modified grounded theory method as shown in the conceptual framework in Figure 1.3.

Pragmatism philosophy is also underpinning this study which underlines the grounded theory research in some ways. According to pragmatism, the truth of an idea lies in its observable practical consequences rather than anything metaphysics, or can be expressed like, “whatever works is likely true, when reality changes, whatever works will also change” (Dewey, 2014). Therefore, truth is unfixed and no absolute or ultimate truth can be possessed. It is a practical approach to help researcher understands complex social process.

Accordingly, its influence can be seen in the grounded theory method, in determining when the saturation is achieved and how coding should be done (Suddaby, 2006). It is in line with the symbolic interactionism characteristic where the process of getting meaning from the phenomenon flows freely from social learning to individual learning and back. What pragmatism and grounded theory have in common is a concern with people's engagement with the world, reliant on detailed observation and insight, followed by never-ending and iterative efforts to comprehend, persuade and enhance (Bryant, 2009).

As stated in the conceptual framework in Figure 1.3, abductive approach is applied in the modified grounded theory method and this is in line with the pragmatism perspective. In this method, the abductive approach is applied during constant comparison and theoretical sampling in determining the saturation level.

3.3 Operational Framework

Figure 3.2 shows the operational framework for this study, which is developed based on the conceptual framework as shown in Figure 1.3. Reviews on the initial analysis of the preliminary and pilot study are rationalized and synthesized to develop an interview protocol for the main study. The interview protocol is then audited by the domain experts for its verification. The primary source for data collection in the main study was semi-structured interview with practicing engineers. An iterative process of interviewing, analysis, comparing and amending the interview protocol appropriately before conducting the subsequent interview is shown in the framework. This iterative process allows the theoretical sampling to be

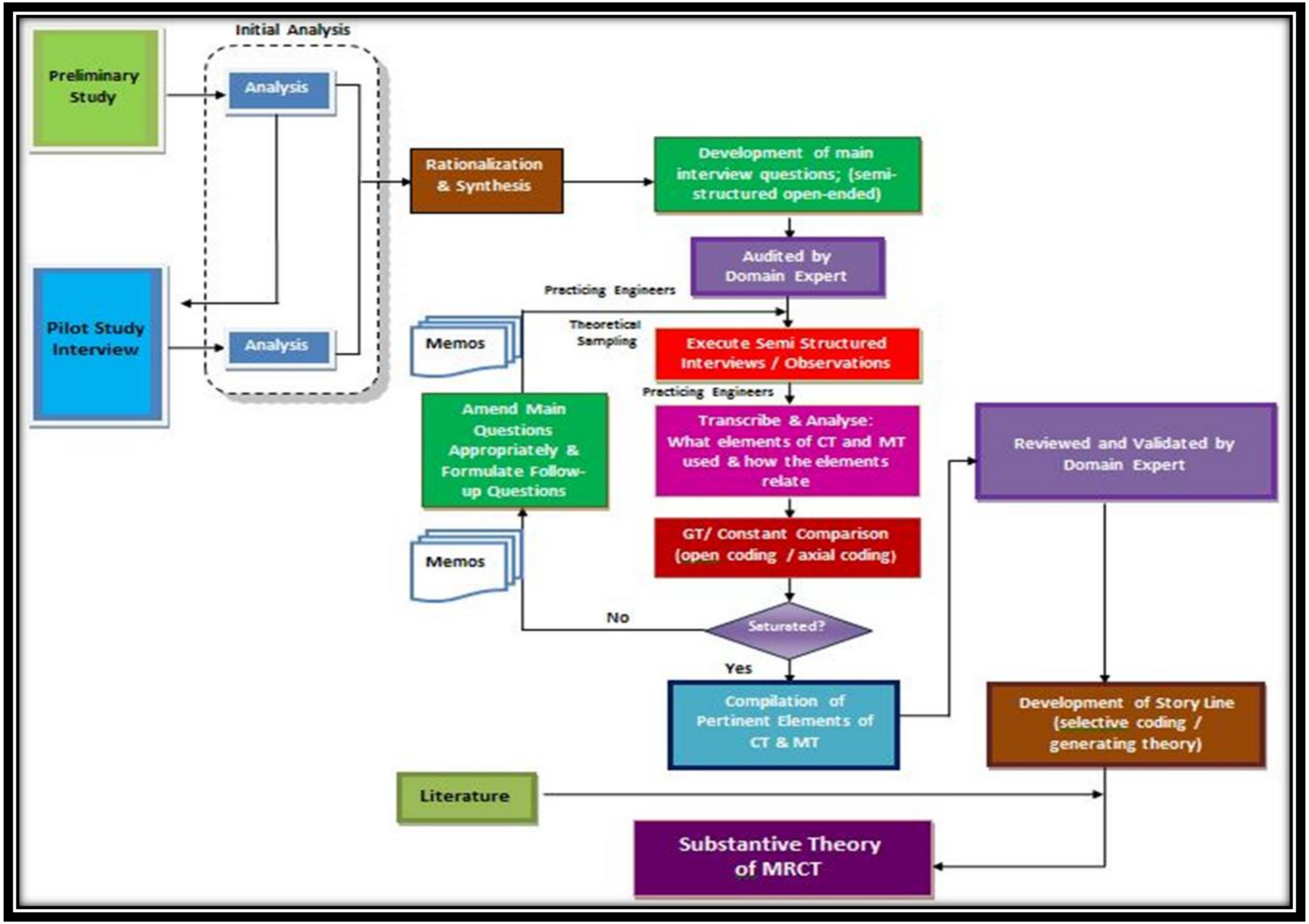


Figure 3.2: Operational Framework

done with constantly comparing the previous data with the newly obtained data from the interviews until a saturation level is reached. Memoing is a vital activity to capture all the thought process and observations reflectively throughout this study.

A list of pertinent elements of critical thinking and mathematical thinking emerged from the coding process is then reviewed and validated by the experts in that particular field to ensure its authenticity. The process is further continued with selective coding analysis for developing story line and eventually developing a substantive theory. At this stage, extant literature can help with concept development and defining properties and dimension of the Core Category. The emerging process theory is a substantive theory of the math-related critical thinking in real-world civil engineering practice. Further detailed explanation about this research operation is discussed in the following section.

3.4 Phases of Research

The process of deriving a general, abstract theory of a process, action, or interaction grounded, involves multiple stages of data collection and data analysis. Data is deconstructed during the coding process for enabling the constant comparative analysis and theoretical sampling to be done (Creswell, 2003). Recognizing the complexity of the study, the research was divided into three main phases namely preliminary study, pilot study and main study. These phases were carried out so as to be able to cover a wide range of study, from the beginning to the end, to judge the feasibility of the study which is a necessary move in a qualitative inquiry (Bogdan & Biklen, 2007).

3.4.1 Preliminary Study

Phase one is the preliminary study, where the sources of data were obtained from the preliminary literature review and previous research.

The greatest advantage of having literature at the early stage of the study is to provide examples of how grounded theory method has been employed in other research. That experiences can give input to the study from the methodological rather than substantive position (Birks & Mills, 2011). Grounded theory is an appropriate approach when there is little extant knowledge of an issue. For that, it is considered relevant to have initial review of literature in order to increase awareness of the existing knowledge base. It is also useful to identify gaps, as well as to avoid conceptual and methodological drawbacks (McGhee, Marland & Atkinson, 2007).

The preliminary literature at the early stage of study was used to enhance the researcher's theoretical sensitivity and to be treated as data (Birks & Mills, 2011; Glaser, 1978). That is, familiarity with relevant literature can enhance sensitivity in identifying and discriminate data significantly. Whereas, the concepts derived from the literature can provide a source for making comparisons with data as long as the comparisons are made at the property and dimensional level, and are not used as data per se (Corbin & Strauss, 2008).

At the preliminary stage, the researcher concentrated on reviewing literature mainly pertaining to critical thinking and mathematical thinking. A review was also done on engineering courses and engineering education, research philosophy and methodology. The reviews helped the researcher to identify gaps in the existing knowledge of critical thinking and mathematical thinking in engineering education.

From that, it forwarded the research to look into the accreditation criteria for engineering courses. Also for any previous research that infused real-world engineering experiences related to critical thinking and mathematical thinking into engineering education, inclining to the accreditation criteria. However, scarcely found any theory or research pertaining to the understanding of the interaction between critical thinking and mathematical thinking in real-world engineering practice.

A study was carried out by Radzi et al. (2012) to get an overview of the nature of civil engineering problems and math-oriented critical thinking skills involved in solving real engineering problems. Interviews and observations were carried out on civil engineers at a civil engineering consultancy firm, on their design work, at construction sites and in their technical meetings. Data in the form of interview transcripts were analyzed using a constant comparative method. The study has identified some of the prevalent trends and challenges of civil engineering problems within the real contexts at engineering workplace. Six categories of the themes emerged from the analyzed data includes not well defined problems, non-engineering-oriented parameters, code of practice-reliant solution, unanticipated problems, other sectors collaboration and past experiences-dependent solution (Radzi et al., 2012). From most of the categories identified, the use of mathematics was widely applied in solving engineering problems even though quite often it was implicitly embedded. The mathematical thinking was significantly essential, together with the critical thinking, are significantly needed to support the analytical ability of civil engineers in interpreting, evaluating, and integrating results. Therefore, they are able to increase the quality of their decisions on arguments in solving engineering workplace problems.

The finding has been showing interrelationship between critical thinking and mathematical thinking in the process of solving civil engineering problems. However, there are still some questions that need to be clarified, such as, what are pertinent elements of critical thinking and mathematical thinking used by engineers in real-world civil engineering practice and how do the elements interrelate and interact? The questions have really driven the researcher to further in-depth investigation into it, to deepen the understanding on the interrelation and interaction between those two types of thinking empirically.

3.4.2 Pilot Study

Pilot study is a mini version of a full scale study, executed to give initial exposure to the real phenomena under study. It accesses the planned data collection and data analysis techniques to naturally help the researcher to better understand the world of civil engineering (Teijlingen & Hundley, 2001). The study aims to frame questions, collect background information, refine a research approach or tailor efficient interview protocol. It has a potential to foresee the weaknesses of the research planning and strategies (Nunes, Martins, Zhou, Alajamy & Al-mamari, 2010).

A semi-structured interview with a practicing civil engineer was executed, based on the purposive sampling method. The purpose of conducting the pilot study was to elicit a bird's eye overview of the real task and nature of work undertaken by a practicing civil engineer (Rubin & Rubin, 1995). As mentioned by Maykut and Morehouse (1994), when the researcher studied and started to analyze the initial data from the pilot study, important or salient dimensions in the phenomenon were observed.

In view of that, the initial information obtained from this pilot interview helped illuminate the path towards the formulation of the main interview protocol. The experience gained through the interview assisted the researcher to refine the interview protocol for the main study. This has consequently increased the likelihood of achieving a productive interview (Maykut & Morehouse, 1994) and having success in the main study (Teijlingen & Hundley, 2001). Several aspects to ponder about the interview protocol have been noted during the pilot study as summarized in Table 3.1.

In grounded theory, this pilot study is deemed vital to pave the way to the main process that focuses primarily on the phenomenon to be addressed (Nunes et al., 2010). To be precise, initial data analysis through open coding and axial coding for the pilot study has resulted in categories that explicate the context. Moreover, open coding has generated categories that support the understanding and development of integrated theoretical explanations of the phenomenon being studied.

Table 3.1: Summarization of Pilot Study Interview Reflection

Things to Ponder		Comments	Justification / Provisional Conclusion
Technical	Interview duration	Two-hour interview is considered quite long. Not a problem for interviewing but very time-consuming for transcribing and analysis.	Allowing prolonged engagement - to establish rapport (Maykut & Morehouse, 1994). Proposed duration : 60-75 minutes
	Interview location	It is very important to be at a place which is conducive and comfortable to conduct interview. To have clear audio is extremely crucial (provided a good audio-recorder is used).	Meet at scheduled time and place. Ensure no potential background noise. Test the tape, replay, and make adjustment as necessary (Maykut & Morehouse, 1994).
Content	By themes	It tends to make the informants feel bored and tired when have to repeat what have been mentioned as different themes may require the same 'story of experience'.	May not be proper to ask questions directly about critical thinking and mathematical thinking. To consider more appropriate ways: asking their experiences handling/ managing a design project; how and what did they do when handling a complex problem. From there, data of interest will be elicited out through coding process.
	By process	This idea may be good for the study. But, the informants may not feel comfortable as they will not be freely expressing and sharing their experiences, when being too confined with the stages of process. Furthermore, the scope of this study does not strictly addressing the data collection against the particular engineering design process.	
	By experience	It is like 'putting all the ingredients in a sack, and then have to segregate them separately'. Quite a laborious task to do, but the informants may feel comfortable with it.	

3.4.3 Main Study

Several activities were carried out in this phase of study such as interviewing, observing and memoing. However, interviews with research informants were the primary data to be collected and analysed. The semi-structured interviews and non-participant observations were carried out at the engineering consultancy firms, focusing on the context of engineering design. Whilst for memoing, it was written throughout the study mainly during data analysis process. A brief description of the aims and executions of these activities is as follows.

3.4.3.1 Semi Structured Interview

Qualitative interview is appropriate when a researcher wants to know how something is happened, or details of the event, or whenever depth of understanding is required (Rubin & Rubin, 1995). The only plausible way to gather data to have insight into the interrelation and interaction between critical thinking and mathematical thinking in real-world engineering practice is by entering the real engineering world and the engineers' perspectives through in-depth, qualitative interviewing (Patton, 2002).

Since this study contextualized critical thinking and mathematical thinking in the particular engineering design process, the research adopted the in-depth semi structured interviews as the primary data collection method. Deriving from the research questions and initial analysis of the pilot interview, an interview protocol, (see Appendix B) for the semi structured interviews were formulated based on the protocol used for the pilot study. The protocol was then reviewed and verified by the experts in the related fields.

Prior to structuring these main interview questions, the researcher had to prepare a reasonably wide reading-up literature on critical thinking and mathematical thinking and some aspects of engineering design process. This is important and essential because having a fairly level of understanding of those existing knowledge enhances the researcher's theoretical sensitivity during data collection and analysis.

Informants of this study comprised of eight practicing and professional civil engineers, who are experienced in civil engineering design for at least five years.

A step by step stages involved in design process from beginning until its completion, were explored during the interview sessions. Each interview session was audio-recorded and transcribed. As data collection and analysis run concurrently, each interview leads to further subsequent interviews as new information and themes emerged from previous interview data analysis (Johnson & Christensen, 2000). Through the theoretical sampling, the appropriate and relevant interview questions and interviewees were determined based on the concepts and categories generated from the data until reaching the saturation level.

Saturation level can be reached as theoretical saturation and sampling saturation (Omar, Hamid, Alias & Islam, 2010). Theoretical saturation happens when data being analyzed show recurring regularities whereas sampling saturation occurs when informants consistently provide the same type of information (Omar et al., 2010). In other words, the saturation level is reached when no more new themes and concepts are emerged from the new data collection. Details of the process are discussed further in data analysis sections.

While these conversations are interpersonal encounters (Johnson & Christensen, 2000) and meant to move beyond surface talk to a rich discussion of thoughts, beliefs and feelings. Time duration for each interview is within one-and-a-half to two hours (Maykut & Morehouse, 1994). This prolonged engagement with interviewees in all qualitative interviews is important to establish rapport and foster a climate of trust (Maykut & Morehouse, 1994; Rubin & Rubin, 1995). However, the duration is still depending on the availability of the informants.

3.4.3.2 Non-participant Observation

The observations on the nature of engineering practice in real-world settings further assisted the researcher in fine-tuning the research and interview questions. The questions were formulated for collecting and validating data throughout the theoretical sampling process. In order to understand the tasks engaged by civil engineers, effort was put as much as possible to observe and follow closely the daily routine work. It includes to observe closely how the engineer calculate, draw rough sketches and interpret results, arrive at conclusions, discuss problems with other engineers in the firm and discuss tasks with other engineers from different disciplines.

In addition, conducting observation was much relevant and essential to the researcher. It reveals a first-hand perspective of civil engineering practice in particular engagement and appropriateness of mathematical knowledge and critical thinking skills in real-world engineering context. The observations on the work of civil engineers were executed at the engineers' office.

Non-participant observation is a method of generating qualitative data. It entails the researcher in the real research setting, to experience and observe directly relevant aspects of that setting. From this, the researcher attains a more intensely personal and intimate endeavor than conducting interviews (Mason, 2002). Nevertheless, non-verbal actions tend to be misinterpreted. Therefore, it is more beneficial, whenever possible and appropriate, to combine the observation with interview to verify the interpretations with informants (Corbin & Strauss, 2008).

Accordingly, in this study, qualitative data generated during observations were digested in interviews with informants and translated into the interview interpretations. In doing this, memoing was very important to record thoughts and experiences along the process of observing and interviewing.

3.4.3.3 Memoing

Memoing is a crucial activity of recording reflective notes or memos about what the researcher is learning during data collection and analysis. It overcomes the tendency of forgetting much that has been experienced or observed (Groenewald, 2008). Writing memo is a process to relate possible sources to sample and to act as repositories of thought in creating an important audit trail of the decision-making process for later use (Birks & Mills, 2011; Corbin & Strauss, 2008).

Memo contributes considerably to the grounded theory method and its trustworthiness (Groenewald, 2008) mainly during the constant comparison and theoretical sampling. In this study, memo was an indispensable reference for the researcher in the process of developing story line and interpreting the emerging substantive theory.

Two types of memoing, namely theoretical memoing and methodological or operational memoing (Groenewald, 2008). Theoretical memoing records attempts to derive meaning from the data. Whereas methodological or operational memoing comprises information along the study as the analysis unfolds such as reminders, tips or comments. A memo can take any form, shape or whatever with no perfection as it has no prescribed structure or format, and without being critiqued or evaluated (Glaser, 2013). The memo is invaluable in lubricating the study as it goes along, mainly during the data analysis process and the writing of it.

Summarization of the research phases and methods is shown in Table 3.2. Data sources and collection techniques are justified according to the phases of research.

Table 3.2: Research Phases and Methods

PHASES OF STUDY	DATA SOURCES AND COLLECTION TECHNIQUES	JUSTIFICATION
PRELIMINARY STUDY Preliminary Literature Review Previous Research	Pertinent Literature Previous Research Report / Articles	Preliminary Literature : • to increase awareness of the existing knowledge base • to identify gaps • to provide info on how grounded theory method has been employed in other research • to enhance the researcher theoretical sensitivity Preliminary Study gives an overview of the nature of civil engineering problems and challenges in general, and image of congruence between critical thinking and mathematical thinking.
PILOT STUDY Interview with a practicing civil engineer.	**Practicing civil engineer** Semi-structured interview Purposive sampling **Memoing** Memo-writing during data analysis	Interview aims to know: • engineering practice i.e. designing a project • a step-by-step process of designing the project • experiences in designing the project • how inferences / conjectures are made and consequences are managed • knowledge / skills requirement to manage the project • other engineering or non-engineering challenges to overcome • detective / preventive / corrective action in designing the project Writing memo to relate possible sources to sample and to act as repositories of thought in creating an important audit trail of the decision-making process for later use

Table 3.2 : Research Phases and Methods - continue

PHASES OF STUDY	DATA SOURCES AND COLLECTION TECHNIQUES	JUSTIFICATION
MAIN STUDY Interview with practicing engineers from two civil engineering consultancy firms.	**Practicing civil engineers** Semi-structured interview Purposive sampling Theoretical sampling **Engineering workplace** Non-participant observation **Memoing** Memo-writing during observations, data collection and data analysis	Same points as mentioned above for the pilot study, with an additional point as follow: • interviews through theoretical sampling allow verification on the findings from previous interviews for the categories generated and for developing dimension and properties of the categories. Observations aim to: • understand better the real-world engineering practice through engineers' social-interaction between/within personnel, working culture, communications, time management etc. • see the sync between the descriptions of tasks explained during the interviews with the real practice. • reveal any info that are not covered during the interview Memoing and observations increase the level of abstraction of ideas while immersing deeper into the process of data collection and analysis, reflexively. A combination of information yielded from different sources and techniques of data collection enables the researcher to capture a higher level of abstraction in developing the substantive theory.

3.5 Informant Selection Criteria

In a grounded theory study, the selection of informant is intentional and focused on narrowing the theoretical sampling to allow the researcher to examine only informants that can contribute to the generation of a theory (Creswell, 2014). Therefore, for this study, a homogenous group of informants was purposefully selected to meet the stated delimiting criteria as mentioned in Section 1.8, Scope and Delimitations. The informants were selected via specific criteria. The informants were chosen from civil engineering consultancy firms, focusing on civil engineering design process. The selected engineers have a minimum of five years' experience in this field of civil engineering design.

In this study, through a theoretical sampling process, a total of eight practicing civil engineers were selected with various years of experience ranging from five to twenty years. The phenomenon of various years of working experience was taken as an advantage for offering multiple stages of design experience and covering wider scope of past and present design experience. All informants who partook in this study were assumed honest in sharing experiences to the best of their memories and remained dispassionate throughout the interview sessions. Informants for this study comprised of experts from two civil engineering consultancy firms in southern region of West Malaysia. These firms were chosen because the data needed for this study could be acquired and the nature of work at these places was coherent with the requirements of the intended research.

3.6 Data Acquisition

Data acquisition was oriented to grounded theory approach, which involved multiple stages of data generation and collection (Birks & Mills, 2011) and the refinement and interrelationship of categories of information (Creswell, 2008). Data generation involves the researcher directly to the data source to produce materials for analysis. Whereas data collection limits the researcher's influence on the data source in the process of data collection (Birks & Mills, 2011). Methods of data generation used in most grounded theory studies are interviews, focus groups and memos (Birks & Mills, 2011). Many grounded theorists rely heavily on interviewing as a way to capture best the firsthand experiences of informants (Creswell, 2014).

Similarly, interviews and memos were the method used for data generation in this study. The primary objective for data generation was to represent the subjective viewpoint of civil engineers who shared their experiences and perceptions on the nature of civil engineering tasks during interviews. Meanwhile, extant literature and other documents and materials from informants were the sources of data for data collection methods.

Data were generated from semi-structured interviews with eight practicing civil engineers. Time duration for each interview was within an hour and two and a half hours, depending on the availability of the informants. The interviews were audio-recorded and transcribed by the researcher. Additionally, data were collected from the pertinent extant literature. Constant comparative method for analyzing data in grounded theory treats the literature as 'data' and repetitively compares it with the emerging categories to be well integrated in the theory. The properties and dimensions brought out from that comparison method were used to examine the incident in the data (Strauss & Corbin, 1998). It determines the orientation of further data generation.

3.7 Sampling

In grounded theory, data sampling is based on the emerging concepts (Corbin & Strauss, 2008). This study used two types of sampling methods, namely purposive sampling and theoretical sampling.

3.7.1 Purposive Sampling

At the beginning of the study, as no emergent theoretical concepts and categories was available to be referred to, initial or purposive sampling method is applied (Strauss & Corbin, 1998). Purposive sampling requires considerable interviewing and observational skills since the selection of informants or observational sites is relatively open (Strauss & Corbin, 1998). There are variations in purposive sampling techniques, thus, it can be executed using different approaches (Patton, 2002, 2014; Strauss & Corbin, 1998). In purposive sampling, informants are chosen with characteristics relevant to the study who are thought will be giving rich information to manifest the phenomenon being studied intensely (Patton, 2002, 2014).

In this research, the purposive sampling was done during the preliminary study and pilot study. Data collected from the preliminary study and generated from the pilot study gave information for selecting informants with purposive sampling in the main study. During purposive sampling, data gathering was not structured too tightly, and the first interview was sketchy and awkward, whereas later ones were much richer in data (Strauss & Corbin, 1998).

In grounded theory, data acquisition and analysis occur simultaneously. Each interview drives the following interviews as new information and themes emerge from previous interview data analysis (Johnson & Christensen, 2000). The emergent categories derived from data determine the orientation of the following interview. Then, potential informants are purposely chosen in view of gathering data related to the properties and dimensions of the targeted categories (Strauss & Corbin, 1998). It is known as doing theoretical sampling. The theoretical sampling is employed from the first interview or data collection (Birks & Mills, 2011). If purposive sampling in grounded theory means where to start, theoretical sampling directs where to go (Charmaz, 2006).

3.7.2 Theoretical Sampling

Sampling method in grounded theory approach follows the principle of theoretical sampling. The evolving categories derived from data of the emerging theory dictates the sampling choices (Corbin & Strauss, 2008; Khiat, 2010). The theoretical sampling determines strategic decision about the most information-rich source of data and questions used to collect data (Birks & Mills, 2011). It is to ensure that the newly developed substantive theory is theoretically complete. This function is an important feature of theoretical sampling (Elliott & Lazenbatt, 2005).

In this study, theoretical sampling was conducted to collect data from practicing civil engineers at two engineering workplaces. The aim was to give the researcher ample opportunities to develop properties and dimensions of the emergent categories. It also included all possible variations in order to identify the interrelation between categories, in regards to critical thinking and mathematical thinking.

The categories generated from data determined the appropriate and relevant interview questions and interviewees. The theoretical sampling was repeated until it reaches the saturation level in which no more new theme and concept emerged from the new data acquisition. This iterative process continues until properties and dimensions of categories under development were saturated with information needed. This study deployed two principle instruments, the Conditional Relationship Guide and Reflective Coding Matrix, for interrelating categories to clarify the process theory. Therefore, the iterative process enriched the categories with relevant information until the Core Category was selected.

Figure 3.3 represents the iterative process of sampling in grounded theory analysis. This figure focuses on showing the connection between initial purposive sampling and theoretical sampling in grounded theory analysis. Theoretical and operational memoing activity, which has been explained in detail in Section 3.4.3.3, was actively carried out along the sampling and data analysis process.

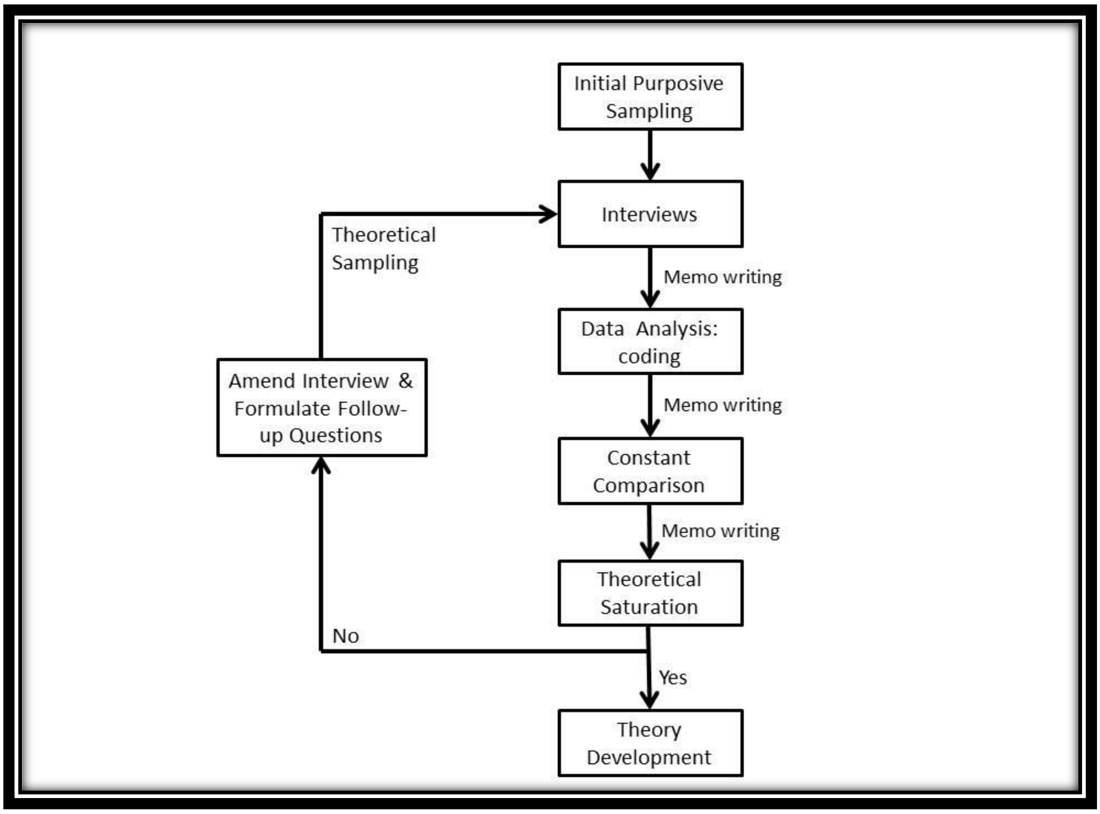


Figure 3.3: Iterative Process of Sampling in Grounded Theory Analysis

3.8 Data Analysis

Data analysis in grounded theory is a fluid and generative process (Corbin & Strauss, 2008). The process started at the moment of initial contact with the phenomenon being studied. It began with coding activity by taking raw data and raising it to conceptual level and continued throughout the development of a grounded theory.

In other words, data analysis was an iterative process where data acquisition and analysis were concurrently run. Those continual activities were to ensure that the developing themes grounded in the original data (Fereday, 2006; Johnson & Christensen, 2000). The most unique part of data analysis methods in grounded theory is the coding process (Johnson & Christensen, 2000). However, it should not be thought of as the analysis in itself and should not be seen as a substitute for analysis that is universally understood across the qualitative research spectrum (Coffey & Atkinson, 1996). Rather, coding encompasses a variety of approaches to ways of organizing, retrieving, and interpreting qualitative data.

The three basic analytic process involved in grounded theory analysis namely open coding, axial coding and selective coding (Corbin & Strauss, 1990; Strauss & Corbin, 1990, 1998). The relation between the research questions and the analytic process in grounded theory analysis in this study is visualized in Figure 3.4.

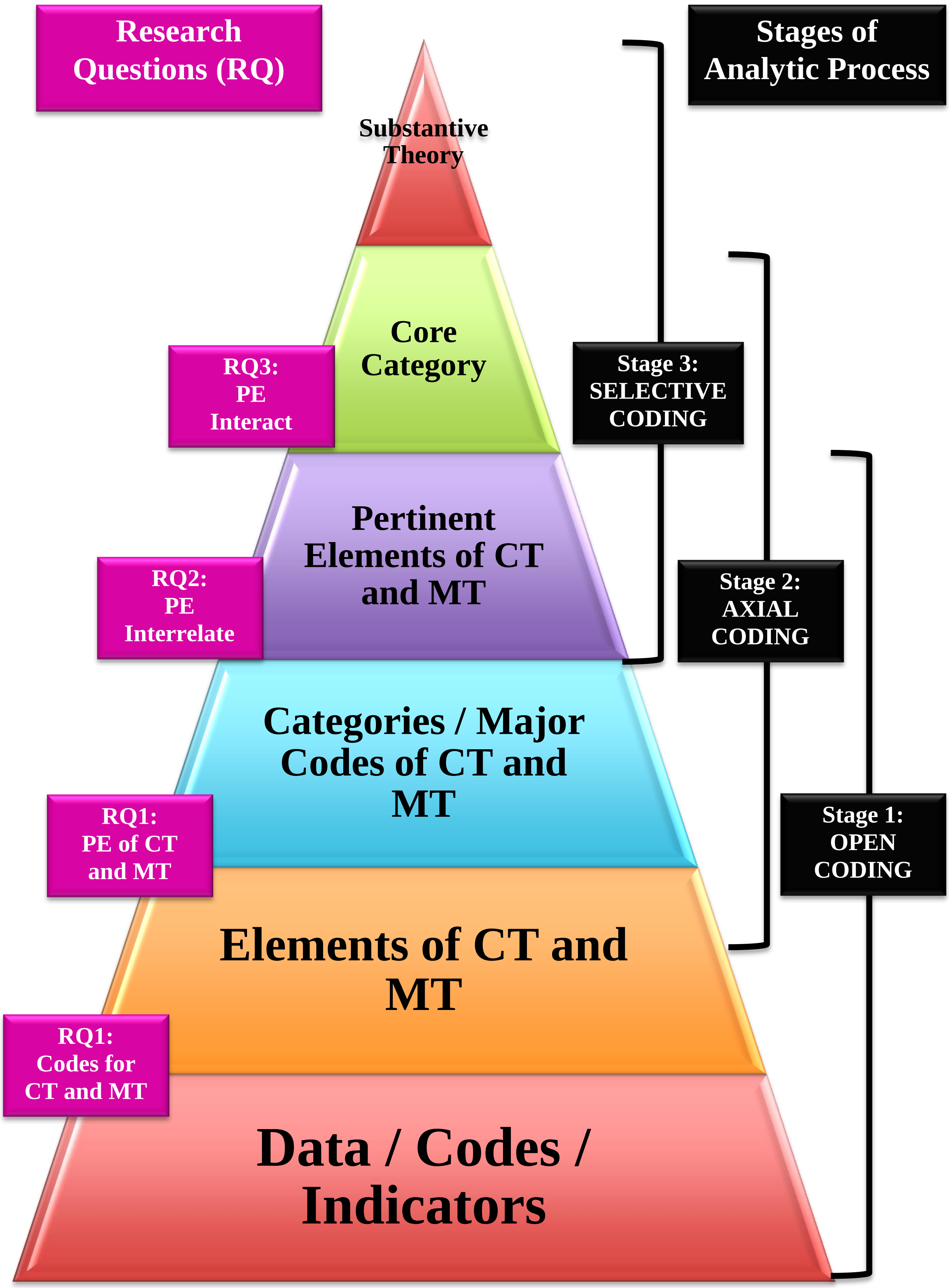
Referring to Figure 3.4, data analysis procedures can briefly be described as below:

a) Stage 1 – Open Coding
   i. Transcribe interviews (data)
   ii. Do data coding (in-vivo/in-vitro codes)
   iii. Identify codes for CT and MT
   iv. Conceptualization: group codes into relevant categories/major codes
   v. Select pertinent elements of CT and MT

This stage of analysis is meant for answering the first research question about identifying pertinent elements of critical thinking and mathematical thinking used by practicing civil engineers in engineering design process.

b) Stage 2 – Axial Coding
   i. Interrelate categories (the pertinent elements of CT and MT) by answering relational questions of what, when, where, why, how and with what consequences
   ii. Establish linkages among categories using a research tool namely the Conditional Relationship Guide

This stage of analysis provides answer to the second research question regarding the interrelation among pertinent elements of critical thinking and mathematical thinking used in engineering design process.



CT: Critical Thinking MT: Mathematical Thinking PE: Pertinent Elements

Figure 3.4: Relation between Research Questions and Stages of Analytic Process

c) Stage 3 – Selective Coding

   i. Select a Core Category from the categories generated. The other remaining categories become the descriptor of the Core Category such as properties, process, dimensions, context and modes for understanding the consequences of the central phenomenon of interest.
   ii. Develop a story line and an emergent substantive grounded theory.

This stage of analysis describes the interaction among pertinent elements of critical thinking and mathematical thinking by determining a Core Category and developing a story line for the central phenomenon of interest in answering the third research question.

Data were analyzed using constant comparative method, and this comparison method relied on the theoretical sensitivity. Coding process was done manually to let the researcher immerse in the data and to have clearer sense of what is going on in the data. Data were analyzed solely by the researcher. However, the analysis and emergent codes and categories were reviewed and verified by the experts in those particular fields to ensure trustworthiness. Microsoft Words 2010 and Microsoft Excel 2010 were used to assist the organization and management of data.

3.8.1 Open Coding (Stage 1)

Open coding is the first stage of data analysis, begins after some initial data have been collected, which involves the labelling and categorization of the phenomenon as indicated by the data (Johnson & Christensen, 2000; Khiat, 2010). It is a way of identifying important words or group of words in the data and then labelling them accordingly using in vivo codes (Birks & Mills, 2011). Nevertheless, in this study, some of the codes were also named after constructs already existing in other theories, if these names seemed to fit best, and when creating new ones would not be practical or justified (Enko, 2014).

According to Strauss and Corbin (1990), open coding is a process of breaking down, examining, comparing, conceptualizing, and categorizing data. Open coding was done mostly by line to line coding to expose the researcher to the complete range of data to gain greater understanding of potential meanings contained within the words used by informants (Strauss & Corbin, 1998). The comparative method that engages the basic analytic procedures of asking questions and making comparisons was used in this open coding process (Glaser & Strauss, 1967; Strauss & Corbin, 1990, 1998) to develop the categories to be more fully in terms of properties and dimensions (Strauss & Corbin, 1990, 1998) .

By using the hybrid approach of grounded theory analysis, inductive and deductive approaches were integrated during the open coding process. Inductive codes were generated by directly examining and interpreting the data, which were embedded in the transcripts of interviews. Deductive approach was applied during the constant comparison process and the selection process of pertinent elements of critical thinking and mathematical thinking. During constant comparison and theoretical sampling, abductive approach was applied in determining the saturation level and how coding should be done, to suit the pragmatism perspective as an epistemological approach. The open coding provided answer to the first research question on what are the pertinent elements of critical thinking and mathematical thinking used in real-world civil engineering practice.

During the early phase of open coding, the researcher might have to diagram or to do a listing, for selecting and relating categories, and later to delineate the properties along with the dimensions. Subsequently, the list could be extended as the analysis progress which provides the foundation that leads to the logic diagrams done during the axial coding (Strauss & Corbin, 1998). For this purpose, a research tool named Conditional Relationship Guide, was used during the axial coding process.

3.8.2 Axial Coding (Stage 2)

Axial coding is an intermediate stage of coding process. Those deconstructed data during open coding were gathered back together in a new form by creating associations between categories, in which, open coding and axial coding go hand in hand (Corbin & Strauss, 2008; Strauss & Corbin, 1990). In other words, axial coding consisted of two ways of operation; firstly was to develop fully individual categories and completely developing the range of properties and their dimensions, and secondly was to link categories together (Birks & Mills, 2011).

The aim of axial coding, together with the memos written during this process, was to interrelate and continue generating categories in terms of their properties and dimensions (Strauss & Corbin, 1998). The memos present answers to the questions of what, when, where, with whom, how, and with what consequences. This is to bringing the process, action/interaction of the area of study into analysis. Although the study reports record in time, the informants continue to interact with their realities (Scott & Howell, 2008) and this dynamic element is known as process (Strauss & Corbin, 1998). Thus, memos help in developing linking among categories.

At the beginning, early written memos reflected only shallow information with uncertainty, misconceptions, and feeble attempts, but with time, the data became clearer and that the content of memos were better in depth and quality of conceptualization (Strauss & Corbin, 1998). Moreover, the important analytic work lies in establishing and thinking of linkages and not in the mundane processes of coding (Coffey & Atkinson, 1996).

In this study, the Conditional Relationship Guide was intensively used to build linkages among the emergent categories. It consists of a table with seven columns. The first column is meant for the emergent categories while the other six columns are intended for the relational questions about the categories. The table was completed by selecting a category and placing the category name in far-left column. This process was applied to all the categories identified in the study. Each relational question about the category (Scott & Howell, 2008; Scott, 2004) needs to be posed into each column to have a clear understanding of a conceptualized phenomenon:

- What is [the category]? (content determination)
- Where does [the category] occur?
- When does [the category] occur?
- Why does [the category] occur?
- How does [the category] occur?
- With what consequence does [the category] occur or is [the category] understood?

According to Strauss and Corbin (1998), when analysts code axially, answers to the relational questions such as what, why or how come, where, when, how, and with what results, uncover relationships among categories. How and why questions are playing important role for describing the chosen Core Category and the central phenomenon that is identified during selective coding (Tuomela, 2005). It was through the axial coding the second research question of this study regarding the interrelation among pertinent elements of critical thinking and mathematical thinking is answered. Apparently, axial coding develops the basis for selective coding (Strauss & Corbin, 1990).

3.8.3 Selective Coding (Stage 3)

Selective coding is the process of integrating and refining categories. It is initiated by deciding on a Core Category, and systematically relating the Core Category to other categories. By doing so it validates those relationships, as well as fills in categories that need further refinement and development (Strauss & Corbin, 1990, 1998). Whereby the Core Category is the main theme of the research (Strauss & Corbin, 1998) and the central phenomenon around which all the other categories are integrated.

There are four criteria for choosing a Core Category; it must be central; that is, all other major categories can be related to it. It must appear frequently in the data; this means that there are always indicators pointing to that concept and the explanation that evolves by relating the categories in logical and consistent. There is no forcing of data and the name or phrase used to describe the central category should be sufficiently abstract so that applicable to other substantive areas, resulting to a more general theory (Strauss & Corbin, 1998).

For this purpose of doing selective coding, the Reflective Coding Matrix was deployed to depict a story line of the patterns discovered in the axial coding through the Conditional Relationship Guide. It was used to develop and contextualize the Core Category. Once the Core Category was identified, all other categories become subcategories, and were known as the Core Category descriptors such as the properties, processes, dimensions, contexts, and modes for understanding the consequences of the central phenomenon of interest (Scott & Howell, 2008). The emergence of these key properties and modes of understanding the consequences was an indicator that the theoretical saturation was going to be reached.

Ultimately, it was during selective coding that explicating the story line, which was integrating and explaining grounded theory (Birks & Mills, 2011; Johnson & Christensen, 2000; Strauss & Corbin, 1990). Accordingly, the explanation answered the third research question on the interaction among pertinent elements of critical thinking and mathematical thinking.

As a conclusion, fundamental aspects of theory development by identifying a Core Category are constant comparison, theoretical sensitivity, theoretical sampling, theoretical saturation and having memos along and throughout the process. The constant comparison incorporates with theoretical sampling in grounded theory analysis. Based on the linkages where constant comparison goes hand in hand with theoretical sampling (Boeije, 2002) and underlying theoretical saturation is the notion of theoretical sensitivity (Morse, 2004), these fundamental aspects of theory development are visualized in Figure 3.5 below.

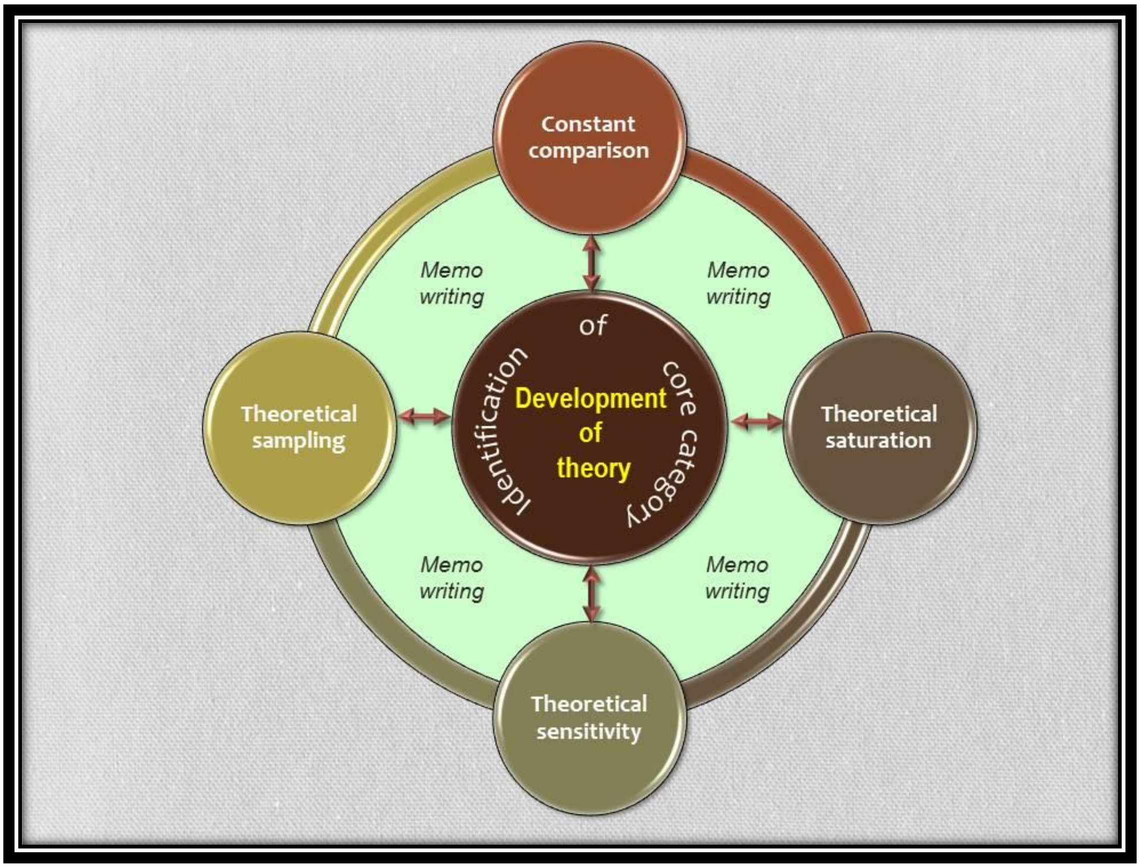


Figure 3.5: Fundamental Aspects of Theory Development

Basically, after each of the data collected, data analysis is immediately conducted and then compared the findings with the previous analysis. While analysing the data, a series of relational questions is asked regarding the findings, influenced by theoretical sensitivity of a researcher. Answers to the questions are sought from the subsequent sampling through theoretical sampling. This iterative process is continuing until it reaches the theoretical saturation. Along the way, the process and thoughts are recorded in memo writing. Thus, data acquisition and analysis are concurrent, and shaped by the theoretical comparison and theoretical sensitivity. Meanwhile, the on-going findings determine the theoretical sampling until it reaches the theoretical saturation.

3.8.4 Constant Comparative Method

Making comparison is essential in identifying and developing categories (Strauss & Corbin, 1998). The comparisons pertain to comparing incident to incident for identifying its characteristics and theoretical comparisons. This comparison process allows the gradual development of data from the lowest level of abstraction to a higher theoretical conception (Strauss & Corbin, 1998). The theoretical comparisons involve the flip-flop technique and the systematic comparison of two or more concepts. Together with theoretical sensitivity which is fostered during the comparison process provide ideas for theoretical sampling to discover variation among data (Strauss & Corbin, 1998). In this study, to meet with the scope of data acquisition and analysis, the comparison process as described by Strauss and Corbin (1998) was moderated and regarded as constant comparative method.

In constant comparative method, data are continually compared to generate theoretical concepts that embrace as much behavioral variation as possible (Glaser & Strauss, 1967). The constant comparative method is applied during comparing incidents applicable to each category, integrating categories and related properties, delimiting the theory, and writing the theory (Glaser & Strauss, 1967; Glaser, 2008).

Constant comparison is part of process of concurrent data acquisition and analysis in grounded theory, involves the constant interplay between the researcher, the data and the developing theory (Johnson & Christensen, 2000). It is a central part of grounded theory. Newly gathered data are continually compared with previously collected data and their coding in order to refine the development of theoretical categories (Gibbs, 2011). Comparison is made between data and data, coding and data, coding and coding, with the previous analysed transcripts helped a lot the open coding process. It ensures the same meaning of interpretation, differentiating codes for the same data segment (multiple codes) or simultaneous codes (applies two or more codes within a single datum), keeping track and avoiding ambiguous guess (Saldaña, 2009). It also enables the researcher to identify emerging/unanticipated themes during the analysis (Anderson, 2010).

In the context of this study, the constant comparison process was intensively carried out during the open and axial coding. Each interview transcript was compared with previous data and not considered on its own, enabling the researcher to treat data from all the transcripts as a whole rather than fragmenting it. After inductive codes and categories were identified during the open coding process, the questions such as what, when, where, why, how and with what result or consequence (Strauss & Corbin, 1998) for each category were asked.

Asking questions and making comparison were essential analytic process used consistently and systematically during analysis process. The process made the categories denser, and eventually its coherent pattern was visualized through the Conditional Relationship Guide. As the researcher plays an active role in this constant comparison process, it is important for the researcher to have theoretical sensitivity, which is fostered in the comparison phase (Johnson & Christensen, 2000; Strauss & Corbin, 1998).

Thus, having constant comparison during data analysis enables the researcher to achieve two major requirements of a substantive theory: (1) parsimony of variables and formulation, and (2) scope in the applicability of the theory to a wide context, while keeping a close correspondence of theory and data (Glaser, 2008).

3.8.5 Theoretical Sensitivity

Theoretical sensitivity is a characteristic of the researcher, involves a mixture of analytic thinking ability, curiosity and creativity (Johnson & Christensen, 2000). It is a form of reflexivity that emphasizes self-reflexive in the processes of developing research questions and doing analysis in grounded theory (Gentles, Jack, Nicholas & Mckibbon, 2014). Glaser and Strauss (1967) has cited the theoretical sensitivity as a two-part concept; personal and temperamental bent, and ability to apply, manipulate and analyze known related existing theory with data in the area of study.

Immersion in the emerging data to improve understanding in the view of what informants see as important and significant, increases level of theoretical sensitivity (Birks & Mills, 2011; Mills & Francis, 2006). Level of sensitivity can be influenced by some factors such as existing literature and prior knowledge, professional and personal experiences, and existing theory (Glaser, 1978). The sources can be used to support the development of categories, but of course the categories should not be forced to fit the literature. Similarly, in this study, the pertinent extant literature and professional and personal experiences of the researcher as explained in Section 3.9, influence the theoretical sensitivity of the researcher.

Furthermore, the researcher does not have to enter the research field with blank mind or tabula rasa, as it often assumed. Having predetermined ideas can enhance theoretical sensitivity by providing concepts and relationships that are checked out against actual data. It enables the researcher to see relevant data and abstract significant categories from the scrutinized data (Glaser & Strauss, 1967).

Constant comparative method for analyzing data in grounded theory treats literature as ‘data’ and repetitively compare it with emerging categories which are then integrated in the theory. The properties and dimensions brought out from the comparison method are used to examine the data (Strauss & Corbin, 1998). Additionally, by doing data collection and analysis concurrently, makes the researcher to become theoretically sensitive to the data. It is the theoretical sensitivity that makes it possible to develop conceptually dense and well integrated theory that is grounded in reality.

3.9 Role of Researcher

In any research, the starting point must be articulation of the researcher's world view because the researcher's own subjectivity influences the research process and output (Austin & Sutton, 2014). It is important to allow readers to draw their own conclusions about the interpretations that are presented in the research findings. To gain a sense of relationship to this study and to be transparent about the own subjectivities, the researcher shared her experiences and background which have given a great impact to the way the study is articulated. As this study adopts the grounded theory approach, the research is underpinned by interpretivist epistemology. Therefore, the researcher plays direct and intimate role in acquiring and interpreting elements of the study and becomes a part of the research (Corbin Dwyer & Buckle, 2009).

As a lecturer teaching mathematics and science to engineering students, the researcher experienced in observing different ways of approaching engineering mathematics learning among the students. This experience has seen the lack of ability among students to apply and integrate mathematics knowledge into other engineering subjects. Students treated mathematics as an isolated subject, confined it in its own boundary.

There was an experience regarding this matter, when the researcher teaching engineering science to the students, for the subject of linear motion. The students found difficulties to do calculations to solve a problem of determining velocity and acceleration for a moving object. Since the students have learnt about differentiation and integration in mathematics, the researcher asked the students to apply that mathematics knowledge to solve the problem. One of the students replied, saying that it was mathematics and different with science. The other students also agreed to the statement.

That was one of incidents that really awaked the researcher that students need to be taught to think critically, particularly in mathematics learning. The students need to be able to think critically to better understand and apply what they have learnt into other engineering subjects. The researcher believes that by having insights into the interrelation and interaction among the pertinent elements, the mathematics teaching and learning can be done in more effective way. Moreover, the perspectives from the lens of engineers in real engineering practice can provide a better understanding to the students of how the knowledge being applied. Thus, it is timely for having insight into the real-world engineering practice about the interrelation and interaction between critical thinking and mathematical thinking, to be incorporated into engineering education.

These prior perspectives of the researcher can bias data acquisition and analysis. On the other hand, it improves the theoretical sensitivity of the researcher in acquiring and analyzing data. While recognizing such methodological limitations due to the prior perspectives, the researcher has taken steps to balance it. For that purpose, the researcher has ensured the emergent categories were solely developed inductively from data. Data were generated from the interviews with the practicing engineers as a way to improve the rigor of the findings. Furthermore, constant comparison plays role in taking care of biases and it is fundamental to grounded theory.

Additionally, the researcher has experience as an analytical chemist about eight years in the quality control department at a pharmaceutical company. Conducting chemical analysis in the laboratory required the researcher to be focused and attentive when dealing with minute of chemical reagents. It required the researcher to think critically and analytically in developing an analytical procedure, designing and testing phases of research and development products. The researcher was responsible in documenting every analytical procedures and reports carefully.

During the research and analysis phases, the researcher had to accurately record all variables, such as type, amount and concentration of chemical reagents, compound components, chemical temperature and test duration. The researcher also had to ensure the quality aspects such as performing standardization for reagents and calibration for analytical procedures and instruments. Apart from fulfilling the requirements, the aim was to enable the results and particulars to be used and referred to brainstorm ideas for new products.

The job has molded the researcher to be a critical and analytical thinker, as well as nurturing good managerial skills. The researcher, where appropriate, have adapted the experiences into this study, mainly during data acquisition and analysis. It increased the level of sensitivity of the researcher in dealing with informants, handling and managing data acquisition and being reflective in writing memo and analyzing interview transcripts.

On the other side, the researcher was not from civil engineering background and has to acknowledge limitations caused by this status. The researcher was not familiar with civil engineering environment and engineering design in particular. While realizing methodological limitations due to this issue, the researcher took some initiative actions to minimize the limitations.

For that, the researcher made engagement with informants for a sufficient period of time. Each interview with individual informants took about two hours. The researcher managed to make the informants speak openly and comfortably by adapting experiences in dealing with professional people from the previous job. The entire source of data was obtained solely through the interviews with the practicing civil engineers.

While realizing that lacking in engineering design knowledge, the researcher has given full concentration on design process explained by the informants. The researcher repeatedly listened to the recorded interviews and inductively coded the transcripts for the design process. These open codes for design process, known as associated elements, as listed in Appendix C were used to help the researcher to have better understanding about engineering design process through the lens of the informants. The elements were then reviewed and verified by the expert in that particular field to ensure its authenticity.

The researcher also kept memos, particularly during the data analysis. The memoing activity was carried out for increasing reflexivity, moderating subjectivity and lubricating the study progress. It was done by capturing ideas, recording insights and describing assumptions throughout the process of data analysis.

3.10 Ethical Consideration

The researcher adheres to some of the techniques suggested by Johnson and Christensen (2000). For this purpose, a consent letter has been prepared as in Appendix D. All informants received and signed consent letters before the interview sessions. The informed consent states the objective of conducting the research and the assurance of anonymity and confidentiality of the informants.

Informants were also assured that no intention to inflict any harm and their participations were voluntary and they might withdraw from the process without repercussion if they were uncomfortable. The informants were explained on the importance of the research and their participations were important for the authentic and reliable data sources for the study.

3.11 Quality and Trustworthiness

Grounded theory involves the use of concurrent data acquisition and analysis, constant comparative analysis, theoretical sampling and memoing. These criteria determine quality of a grounded theory research and promote quality standards through research practices in grounded theory methodology (Elliott & Lazenbatt, 2005). Showing complete transparency in the data collection process enables to demonstrate trustworthiness, which is important to ensure quality in grounded theory studies.

Strauss and Corbin (1990, 1998) set the criteria for assessing the quality of research for grounded theory into eight conceptual questions.

i. Are concepts generated?
ii. Are concepts systematically related?
iii. Are there many conceptual linkages and are the categories well developed? Do categories have conceptual density?
iv. Is variation within the phenomena built into the theory?

v. Are the conditions under which variation can be found built into the study and explained?
vi. Has process been taken into account?
vii. Do the theoretical findings seems significant and to what extent?
viii. Does the theory stand the test of time and become part of the discussions and ideas exchanged among relevant social and professional group?

These criteria for assessing the quality of empirical grounding of grounded theory can be complemented by ensuring the four main indicators of trustworthiness from the interpretive worldview are fulfilled (Cho & Lee, 2014). Gasson (2003) has compared four main indicators of trustworthiness between positivist and interpretive worldviews as outlined by Lincoln and Guba (2000) and Miles and Huberman (1994). They are objectivity, reliability, internal validity and external validity for positivist world view and correspondingly, confirmability, dependability/auditability, credibility and transferability for interpretive world view. Table 3.3 shows an overview on strategies to establish aspects of trustworthiness used in this study with its explanation as follows.

Confirmability shows the findings depend on the phenomenon being studied and informants rather than the researcher. It is sometimes called as 'external reliability' when referring to the quantitative terminology. In other words, it is relative neutrality or the extent to which the findings of a study are formed by the informants with reasonable freedom of researcher's biasness, motivation, or interest (Miles et al., 2014). In this study, the researcher demonstrated the confirmability by having memos as reflexivity to moderate subjectivity, triangulation of data and codes through constant comparison and also having an audit trail.

Dependability is about repeatability and consistency of the research process, which is reasonably stable over time between researchers and methods. It refers to the reproducibility of the findings (Elliott & Lazenbatt, 2005). For this, the researcher practiced some exercises: 1) ensuring the congruence between the research design and the research questions by having memos as reflexivity to capture ideas, connections and methodological notes related to the understanding of the

Table 3.3: Strategies to Establish Aspects of Trustworthiness

Trustworthiness	Confirmability	Dependability	Credibility	Transferability
Definitions	Findings depend on the phenomenon being studied and participants with reasonable freedom of researcher's biasness, motivation, or interest. (Miles et al., 2014)	Repeatability and consistency of the research process referring to the reproducibility of the findings. (Elliott & Lazenbatt, 2005)	It is about confidence in the 'truth' of the findings and congruency between research findings and reality. (Merriam, 2002)	Findings have applicability and fit in other contexts (Miles et al., 2014)
Strategies	Reflexivity (the use of memos to moderate subjectivity) Triangulation of data and codes through constant comparison Audit trail (maintaining detailed documentation of the methods and the collection and analysis of data)	Reflexivity (having memos as reflexivity to capture ideas, connections and methodological notes in ensuring the congruence between the research design and the research questions Audit trail (maintaining detailed documentation of research including the list of informants, audio records and interview transcripts and documents of coding process)	Constant comparison and Theoretical sampling along the process of data acquisition and analysis Prolonged contact with informants around the phenomenon of interest Expert reviews of data and findings Theoretical saturation (no more new theme and concept are emerged from the new data acquisition).	Rich, thick description derived from data in deriving a theory (multisite designs - the selection of informants and research setting includes sufficient variations; for example, in this study, informants were selected from two different civil engineering consultancy firms)

phenomenon 2) maintaining detailed documentation of the methods and the collection and analysis of data as an audit trail of this study (Merriam, 2002). The audit trail included the list of informants, audio records and interview transcripts, documents of coding process and memos.

Credibility indicates internal consistency of the research findings to the informants and to the readers. It is about confidence in the 'truth' of the findings and congruency between research findings and reality (Merriam, 2002). It also concerns about authenticity where the findings should portray the significant elements in the research context. Thus, this research demonstrated credibility by having constant comparison and theoretical sampling along the process of data acquisition and analysis, prolonged contact with informants around the phenomenon of interest, expert reviews of data and findings, and theoretical saturation.

Transferability shows the findings have applicability and fit in other contexts (Miles et al., 2014). In the qualitative sense, providing rich, thick description is a major strategy to ensure transferability (Merriam, 2002). It was demonstrated in this study by having rich, thick description resulting from data in deriving a theory. Additionally, the selection of informants and research setting includes sufficient variations and was fully described for relative comparisons with other samples. For example, in this study, informants were selected from two different civil engineering consultancy firms and it is called as multisite designs or maximizing variation in the purposely selected sample (Merriam, 2002). Applying constant comparative method throughout data analysis process enhances transferability of a theory (Glaser, 2008). A substantive theory may delimit its application to other contexts if a constant comparative method of modifying the theory is neglected.

It is not recommended to verify the emergent theory with the informants as is usual in narrative research designs (Moghaddam, 2006). According to Glaser (2002) inviting informants to review the theory for whether or not it is their voice is wrong as a 'check' or 'test' on validity. Grounded theory is mostly based on the researcher's interpretations, generated from much data and investigated a phenomenon in the real world through the lens of the researcher. Furthermore, grounded theory is not their articulations, but it is generated as an abstraction from their doings and their meanings that are taken as data for the conceptual generation. Therefore, they may not aware it empirically and may not understand it literally (Moghaddam, 2006).

In grounded theory, the representativeness and consistency are achieved through the theoretical sampling (Corbin & Strauss, 1990). However, the representativeness of the concepts, and not of the persons, that is important. This is because the aim is ultimately to build a theoretical explanation and not to generalize findings to a broader population per se.

3.12 Summary

This chapter presented a detailed outline of the research methodology of this study. The discussion focused on philosophical and methodological stance, and the methods employed to achieve the research goals by describing several aspects of research design as follows:

a) Section 3.2 explained the research philosophy about the way in which the researcher views the world. Theoretical paradigms underlying this study were highlighted as interpretive/symbolic interactionism and pragmatism with the philosophical inclination embedded more significantly and seminal in Strauss and Corbin’s version of grounded theory.

b) Sections 3.3 and 3.4 described the operational framework and three phases of research involved in this study, namely preliminary study, pilot study and main study. The description stated that the purpose of implementing the phases was to cover a wide range of study in recognizing its complexity. It explained about strategies carried out during the main study such as conducting semi-structured interview with the practicing engineers, non-participant observation and memoing. These particulars were then visualized in Table 3.2 for the summarization of research phases and method and in Figure 3.2 for the operational framework of this study.

c) Sections 3.5 and 3.6 explained about informant selection criteria and the acquisition of data in this grounded theory study. The explanation was based on methods of data acquisition through data generation and data collection. It mentioned that data were generated from semi-structured interviews with eight practicing civil engineers from two different civil engineering consultancy firms. Whereas, for data collection, the extant pertinent literature was treated as data in constant comparative method for analyzing data in grounded theory.

d) Section 3.7 focused on explaining about sampling methods involved in this study. It explained about purposive sampling and theoretical sampling related to the phases of research.

e) Section 3.8 presented detailed information regarding strategies in data analysis. The section explained in detail about open coding, axial coding and selective coding. It was then followed by the discussion of two important characteristics of grounded theory namely constant comparative method, which is the central part of grounded theory, and theoretical sensitivity as a characteristic of the researcher that influences the articulation of a substantive grounded theory.

f) Sections 3.9 to 3.11 presented another several aspects of methodology. These sections discussed the role of the researcher that has given a great impact to the way the study is articulated and ethical consideration related to the interview process. Also, a section discussed the quality and trustworthiness of this study involving confirmability, dependability/auditability, credibility and transferability.

The next chapter defines details of the data acquisition over the period of study and also as an expansion of the data acquisition approach described in this Chapter 3.

CHAPTER 4

DATA ACQUISITION

4.1 Introduction

The previous chapter presented data acquisition approach. As an expansion from that, this chapter presents full information about data acquisition by describing in detail the process of locating interviewees and interviewing settings and strategies, some relevant aspects of reflexivity, steps taken for transcribing interviews, memoing and obtaining extant pertinent literature as data collection. This chapter has been organized as depicted in Figure 4.1 below.

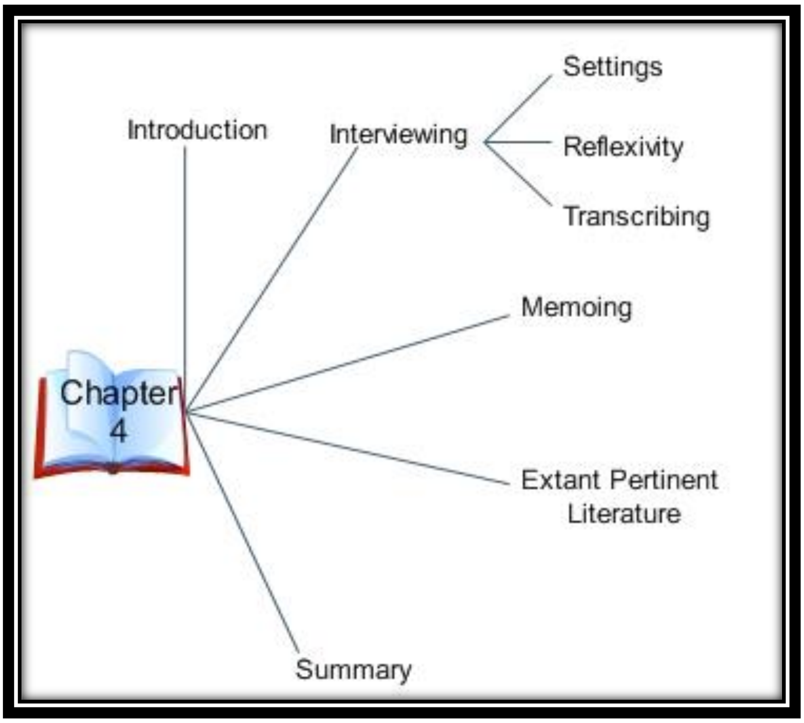


Figure 4.1: Thematic Structure of Chapter 4

4.2 Interviewing

Interviews formed the basis for the research. Interviews were the main data source for coding activities which subsequently leads to the emergence of theory. Three important aspects involved in the interviewing process are discussed in the following sections.

4.2.1 Settings

Finding professional and practicing engineers to be as informants for this study was a challenge for the researcher. It was a challenge to have informants who fit the study criteria and to allocate their time for about two hours for the interview. The researcher gathered some relevant information from colleagues and civil engineering experts at the faculty and started to arrange for appointments with the informants.

Initially, the researcher planned to collect data from one consultancy firm considering its reputation and capacity would sufficiently provide data needed for this study. However, after the fifth interview, an emergent pattern of the data collected could already be seen. Therefore, the researcher decided to collect samples from another firm to demonstrate trustworthiness mainly for ensuring the credibility and transferability of the research findings.

The first consultancy firm approached has six engineers with different background of experiences and length of service. Two of them are professional engineers who have about twenty years' experience in civil engineering design. The other two senior engineers have more than ten years' experience in engineering design. The other two practicing engineers, who previously worked in civil engineering construction, have also been in civil engineering design for more than five years. All the six engineers were the informants in this study and appointments with those engineers were set through one of the professional engineers, who was also a director for the company.

On the other hand, another consultancy firm has three engineers and only two of them were interviewed for this study. One of these two engineers was a professional engineer, who has about fifteen years' experience in engineering design and the other one was a practicing engineer with about eight years' experience in this field.

The first appointment was arranged through a telephone call. This first appointment was made purposely for having a meeting with one of the directors of the company to discuss procedures for conducting interviews with other engineers in that company. The director, who is also a professional engineer, mentioned the preference about how the future interviews to be held with the other engineers.

According to the director, all interview appointments with other engineers in the company must be set with the director through telephone calls. Only upon the director's approval, the interviews could be held. All the interviews must be conducted in the office of the company. Additionally, the researcher was allowed to audio-record the interviews.

After discussing the procedures for conducting interviews, the researcher would like to make an appointment for the next interview with the first informant of this study. Unexpectedly, the director decided to be the first informant and asked the researcher to start the first interview right away. Luckily the researcher came for the meeting with all relevant documents needed for interview. Therefore, the first informant for this study was a well-experienced professional engineer cum the director of the company. The interview was done on a one-on-one basis for about two hours.

Three weeks prior to the first interview, the second appointment was fixed. Upon reaching the interview location, the researcher was informed that there were two engineers available to be interviewed. The appointment was made to meet with one of the engineers, but there was a sudden change and request by the engineers to be interviewed on the same day. As a researcher who wanted to gather information from informants, any reasonable request for the informants' comfort and availability was taken into consideration. Hence, the interview was conducted with both engineers, one after another, but with the presence of both of them during the whole interview session.

At first, the researcher asked a few questions to one of the engineers and then followed with another one for the same questions. Then, the researcher continued with the remainder of the questions with the same pattern of interviewing. However, the researcher encountered some difficulties when conducting the interview in that particular way. Since most of the sub-questions were based on the informants' answers, the researcher might have forgotten the questions being asked to the former informant when interviewing the latter. Furthermore, the presence of both engineers at the same time of interviewing but were not being asked at the same time for each questions, allowing some negligence during the interview.

The third appointment was arranged about a month after the second interview session. Again, two engineers were attached to the appointment. Since it was set by the director who was responsible in arranging the appointment, the researcher accepted it unconditionally. The experience from previous interview with two informants was taken into consideration. Therefore, the researcher changed the way of interviewing these informants whereby the informants were asked the same question simultaneously. They answered it one after another and occasionally at the same time. This approach allowed the interviewees to have a time lag to think of what to say when the other was talking, and sometimes giving ideas or reminding each other of things to share.

As mentioned, the researcher started conducting theoretical sampling right after the first interview. However, the main idea addressed in the interview protocol was still being followed, while focusing on the aspects as emergent categories from the previous interview.

Interview with the sixth informant was conducted at the other consultancy firm. The appointment was made through a telephone call about a month after the previous interview. The informant was a professional engineer.

Three weeks after the interview, another appointment was made with the seventh informant, who was a professional engineer from the first consultancy firm. The eighth informant was interviewed two weeks after that previous appointment, at the second consultancy firm.

The researcher stopped at the eighth informant when the data was found to be saturated and showed recurring consistencies and no new category emerged. The researcher realized after the fifth interview that the informants were consistently providing the same pieces of information.

Figure 4.2 illustrates the flow of data acquisition and data analysis toward saturation of categories.

In summary, the informants consisted of two professional engineers cum directors of the company, one professional engineer, two senior engineers and another four engineers with five to twenty years' experience in engineering design. The duration of interviews were recorded between sixty three to one hundred and fifty minutes.

Table 4.1 shows the professional profile of informants from both consultancy firms with alternate names for anonymity and the duration of interviews.

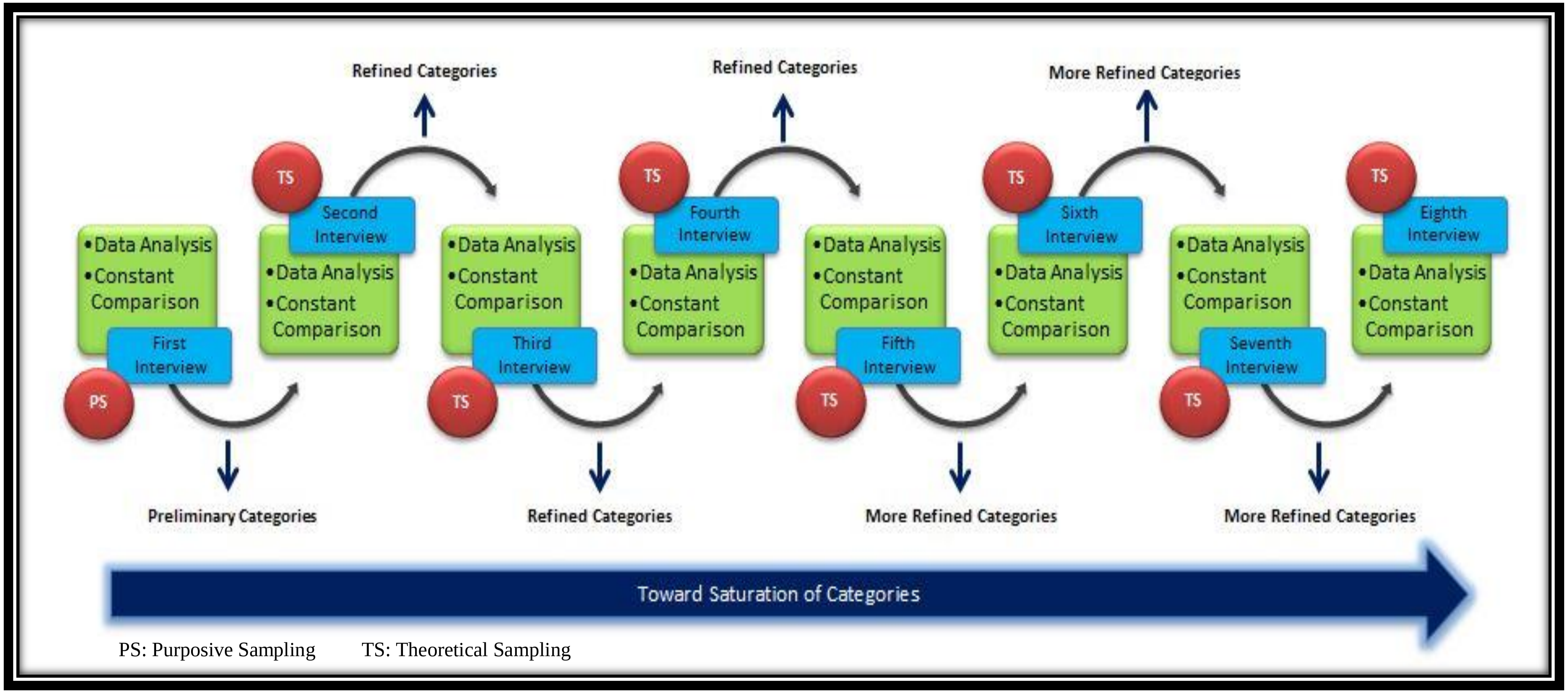


Figure 4.2: The Flow of Data Acquisition and Data Analysis toward Saturation of Categories

Table 4.1: Professional Profile of Informants and Interview Duration

Site	**Informants**	**Gender**	**Designation**	**Experience in Engineering Design (Years)**	**Duration of Interview (Minutes)**
Firm A	Engineer 1 (E1)	Male	Professional Engineer, Company Director	20	85
Firm A	Engineer 2 (E2)	Female	Engineer	6	82
Firm A	Engineer 3 (E3)	Female	Engineer	5	82
Firm A	Engineer 4 (E4)	Female	Senior Engineer	15	150
Firm A	Engineer 5 (E5)	Male	Senior Engineer	15	150
Firm B	Engineer 6 (E6)	Male	Professional Engineer	15	63
Firm A	Engineer 7 (E7)	Male	Professional Engineer, Company Director	20	107
Firm B	Engineer 8 (E8)	Female	Engineer	8	85

4.2.2 Reflexivity

Qualitative researchers regard interviews as interactive meaning-making and are interested in the process of how meanings are produced within areas of study (Edwards & Holland, 2013). Reflexivity makes the research process itself as a focus of inquiry that requires reflection on the entire research process. In view of that, each interview process taught its own lesson.

As mentioned above, the first informant was a well experienced professional engineer. The informant explained about civil engineering design in a considerably broad view. It enabled the researcher to have a comprehensive overview about design process and its challenges and problems. For the subsequent interview, where the first theoretical sampling began, the researcher focused on aspects of design such as water and sewerage infrastructure and structural design, as repeatedly mentioned in the first interview. The researcher interviewed two engineers who are responsible in infrastructure and structural design particularly.

The main conceptual idea generated from these first three informants was that good communication was very important in carrying out the design process. If software accelerates the design work, communication and team work smoothen the flow of design process. Briefly it can be concluded that software, communication and team working are important elements to be considered along the way of design process.

The goal of this study is to understand the interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice. Data obtained from the third interviewee was somewhat surprising since what was perceived by the engineer regarding critical thinking and mathematical thinking fit for answering the research questions of this study. The engineer firmly stressed that critical thinking and mathematical thinking must be applied concurrently along the design process. The engineer also mentioned that having critical thinking in mathematics instruction is timely and necessary. These findings made the following interviews more focus and directed. After having the fifth interview, the researcher found that it was almost reaching the sampling saturation when the informants repeatedly mentioning the same information.

The interview was continued with the sixth interviewee and it was totally different with the previous interviews in term of the way it was conducted. The interviewee was a professional engineer with about fifteen years' experience in engineering design process. The interview session with the interviewee was treated like a validation process in which the questions posted were about the categories emerged from the previous interviews. The decision to change the style of interviewing was made as soon as the researcher noticed that the interviewee was comfortable answering questions rather than sharing experiences. Since the interviewee was an experienced professional engineer, the researcher did not want to lose the opportunity to grab as much information as possible. Therefore, the researcher manipulated the situation to verify findings from previous interviews. Fortunately a report of findings from the previous interviews was available with the researcher and it was a smooth session of interviewing. The interviewee was comfortable with that approach and the interview provided a baseline of trustworthiness to the findings.

Findings and experiences obtained from the past interviews fueled the researcher to continue conducting another interview even at that time the sampling and theoretical saturation level was almost completely reached. If not for eliciting new categories, subsequent interview could serve as a platform for verification of the previous emergent categories. Either way, the decision to continue theoretical sampling would be beneficial to this study. Hence, the subsequent interviews were conducted with the seventh and eighth interviewees from two different consultancy firms. The interviews yielded fruitful insights by providing deeper and richer information related to the emergent categories from the previous interviews. However, no more new categories or themes were identified. Therefore, the researcher determined to stop sampling at this point.

4.2.3 Transcribing

The researcher audio-recorded and transcribed all interviews. Transcribing interviews and coding the transcripts need a lot of patience and concentration. Each interview was transcribed and coded prior to interviewing the following informant. At first, the researcher listened to the recorded interview several times to capture the conceptual ideas before starting transcribing and coding.

All interviews were transcribed using google application named oTranscribe. The application enabled the researcher to: 1) Listen and transcribe an interview at the same time, on the same page provided by oTranscribe as no switching between quicktime and Word. 2) Pause, rewind and fast-forward without taking hands off the keyboard. 3) Interactive timestamps to navigate through interview transcript with. 4) Automatically saved to browser's storage every second. All transcripts were saved in Microsoft Words 2010 documents and retrievable for analysis and audit purposes. Together with Microsoft Excel 2010, the transcripts were analyzed, organized and managed. An operating procedure on how to use the application is described below:

i. Click the link http://otranscribe.com/
ii. Click ‘start transcribing’
iii. Click ‘choose audio file’
iv. Choose audio file that want to be transcribed
v. Now, start to listen and transcribe at the same time, on the same page.
vi. Adjust the speed meter according to the desired ‘tempo’
vii. Click back or forward arrow when necessary
viii. Save it. Note: The transcription is in the text doc (.txt).

To convert the file to Word document (.doc):

i. Open Microsoft Word file
ii. Open the .txt file in the Microsoft Word
iii. ‘save as’ the .txt file as .doc

4.3 Memoing

Memoing is an activity consisting of writing down ideas and thoughts along the process of conducting research. Memo is living and working document as when an idea occurs, the researcher pauses and records it. When a researcher writes memos, the process of analysis occurs in thinking and is then visualized in writing. The researcher engaged in this on-going process that involves a continual internal dialogue (Strauss, 1987).

This section represents excerpts and examples of memos recorded in this study. There were two sets of memo written by the researcher: general memo (methodological memo) and memo for coding process (theoretical memo). General memo was to reflectively capture outflow of ideas, insights, observations and assumptions along the study. Whereas, for coding process memo, it captured almost all the thought process throughout the coding process such as comments, reminder, tips, attempts for deriving meaning from data and relating provisional relationship between codes and/or categories. Memoing was actively practiced in this study during data collection, data generation and data analysis.

Data collection: From the beginning when the researcher started reading pertinent literature regarding critical thinking, mathematical thinking and grounded theory, memoing activity was already initiated. Below is an example of memo that was written during the initial literature review.

> *"CGT suits for research exploring new area of study or very little studies have been done on it. So, someone can start the research by going to the field, make some interviews and observations, until concepts emerged from it. Then, concentrate on a main concern and not all of the concerns. Why? Because what going to be reported is the conceptual, and not the descriptive theory. Here, theoretical sensitivity of the researcher is important. Therefore, there is no need for audio-taping and transcribing interviews in doing CGT. It's just like watching movie, we don't have to memorise details of the script but just understand the story concept to be able to re-tell the whole story. But,*

is it practical to be done for a PhD student when there is no evidence to keep, no reference to refer to for doing re-coding and re-analysing data. I do not feel so safe for doing like that. Another point, it is important to enter into the field with openness. We may have certain expectations, but we must put it aside and allow the concerns of the informants to emerge. That is an essential part of CGT. Therefore, no specific RO/RQ in CGT, no philosophical underpinning and no theoretical perspective of the research. Hmm, I really have to think over it if want to adopt this CGT.

Meanwhile, for the contemporary GT, some ideas about area of interest have been studied. Research is going to explore and uncover a process/event/ situation/phenomenon with is embedded in the field, and related to the pre-existing theories. In my research, I would like develop a substantive theory pertaining to CT and MT, in the sense of understanding the interaction between these two types of thinking during the execution of civil engineering practice. So, during open coding process, from all the codes assigned, I have to 'search' for the codes pertaining to my study interest, which are related to CT and MT. I need a pre-empirical conceptual determination in order to guide the search for data and decrease the risk for unfocused data collection. Usually, other than CGT, they call it as QDA and for the ground theorists, only CGT is considered as GT. So, if a research starts with having philosophical underpinning, theoretical perspective(s), specific RO/RQ, then, it is not called as GT but modified GT..!"

Data generation: A memo was written after each interview session. These memos captured ideas emerged in the interview sessions either during conversations or through observations. Here are excerpts of a memo written during data collection:

"He was at a 'different' level of thinking, giving views in more general forms. He was not so 'good' and seemed not comfortable in sharing experience. Most of the time when asking him about his experience, his replied was "hmm, macam mana ehh nak explain"("hmm, how to explain ehh"). As a result, it was hanging completely unexplained. I realized that I need to do

something. I could not just let the opportunity goes like that as I knew he was a well experienced professional engineer. I noticed that he could answer questions very well if I injected some information as a 'starter'. So, I guessed it was a good chance for me to 'verify' findings from the previous interviews. Luckily I had the findings report with me and of course also in my head. He seemed comfortable. Fortunately the interviewing session was successful, and fruitful. He explained and emphasized more the design steps, the flow of the process and about interaction between design team."

"It was good having this interview with him for 'verifying' and 'validating' what I have had from the previous interviews. He strengthened my understanding to see and to understand their practice in more organized way. Maybe it was due to his position as PE, as well as 'strong man' in the company. However, not much new info about the elements of CT and MT could be obtained from his own experience as he did not tell much what he has actually done, but more on how the design process is done in his company. I guessed it suits the purpose and intentions of the theoretical sampling."

Data analysis: Memos were actively written during this phase of study. It covered a wide range of data analysis process such as open data exploration for each transcript analysed, developing properties and dimensions of categories, making comparisons and asking relational questions during coding process, elaborating paradigm, selecting a Core Category and developing a story line. The following are excerpts from the memos written during data analysis.

"Analysing this kind of transcript is not easy…I need to 'put and train' my thinking in two different forms. First round, I read and re-read the transcript. I looked into the transcript as if 'immersing' myself into their world. I 'conceptualized' their tasks in appropriate themes. Second round, I analysed it as an 'observer or evaluator' in determining CT and MT elements used in their practice. As a result, I got some themes for the practice, more on building dimension and properties of the previous themes, as well as some

elements of CT and MT used in their practice, even not as much as from previous interviews."

"From both transcripts of Engineer 1 and Engineer 2, have been showing that having communication is very important in carrying out their tasks. If software accelerates the design work, communication and team work smoothen the flow of design process. So, briefly can be concluded that software, communication, team working…are elements to be considered along the way of design process."

"Today I am doing full analysis on transcript of Engineer 7. I could see some similarities in his and Engineer 6's ideas. Both were talking about 'creativity' and 'short cut' in designing. So, my conclusion, these two guys have much confidence in themselves about designing. They put the design process into four stages…beginning, preliminary stage, designing and final stage."

"Obviously the usage of MT in the real practices totally different with that in the classroom. If in the classroom, the MT is domain related, which is related directly to mathematics, where as in the real practices, it is used in the form of application of it."

All memos are kept auditable and applicable in a softcopy form in two different files in Microsoft Word 2010 to demonstrate an audit trail.

4.4 Extant Pertinent Literature

Since this study uses perspective of Facione for critical thinking and Schoenfeld for mathematical thinking as explained in Chapter 2, relevant information from these two perspectives were adopted into this study. The particular information applied in this study was the core skills and dispositions of critical thinking and five aspects of cognition of mathematical thinking. As mentioned earlier in the previous chapters, the adoption of this existing knowledge aimed for minding the abundance of data collected in this study. The information from extant literature was not incorporated as data per se but for comparison with the emerging categories during constant comparison process throughout this study. This information was used in open coding during the selection and categorization of pertinent elements of critical thinking and mathematical thinking. Also, it was used in axial coding during interrelating and developing properties and dimension of categories, and in selective coding during developing story line of the emerging theory.

4.5 Summary

This chapter explained in detail about data acquisition as follows:

a) Section 4.2 thoroughly described the process of locating and interviewing eight engineers from two engineering consultancy firms. It explained the interviewing setting and strategies for the arrangement of appointments and approaches applied for interviewing. It also explained about reflexivity throughout the interviewing process and transcribing procedures using the google application.

b) Section 4.3 presented examples of memos written along the research process mainly during data collection, data generation and data analysis.

c) Sections 4.4 highlighted the stance of existing knowledge from the extant pertinent literature in this study. It has been incorporated into the grounded theory analysis mainly for constant comparison process purposes.

Since data acquisition and analysis worked hand in hand, the next chapter describes details of data analysis activities.

CHAPTER 5

DATA ANALYSIS AND EMERGING THEORY

5.1 Introduction

This chapter presents a comprehensive explanation about data analysis and development of story line of the emergent substantive theory. The data analysis happens at textual and conceptual levels (Groenewald, 2008) which are explicitly explained in grounded theory analysis. In this study, textual level entails reading the complete data of interview transcripts and memoing throughout which is mainly done in open coding. For the conceptual level, it involves theorizing about categories, properties and dimensions of the categories and interrelation among the categories. In grounded theory analysis, this conceptual level is often referred to as axial coding together with the written memos of the analysis process.

This chapter begins with a section explaining about constant comparative method which is carried out throughout the analysis process. According to Strauss and Corbin, there are three basic analytic process involved, namely open coding, axial coding and selective coding. Details of the three stages of analytic process are discussed in the following sections. The next section explains about the development of story line of the emerging theory. This section discusses in detail all the six processes related to the refined Core Category which are identified during selective coding namely *complying requirements, forming conjectures / assumptions, drawing reasonable conclusion, defending claims with good reasons, giving alternative ways / solutions and selecting / pursuing the right approach*.

The representation of conditional matrix, which visualizes the emerging theory, is discussed right after the section of development of story line. Figure 5.1 shows the thematic structure for the organization of this chapter.

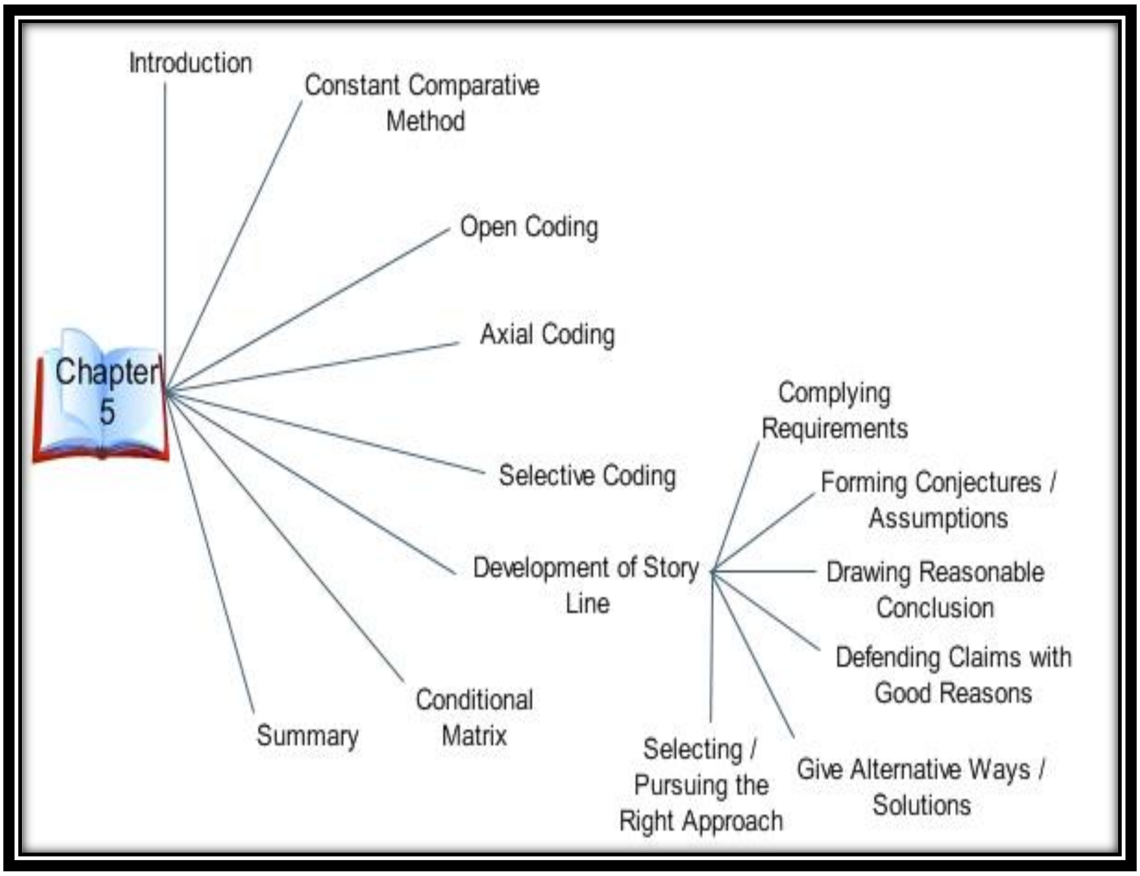


Figure 5.1: Thematic Structure of Chapter 5

Figure 5.2 shows an overview of data analysis process. Arrows in the figure represent the constant comparison process. This figure becomes the main reference in explaining about data analysis and emerging theory throughout the discussion in this chapter.

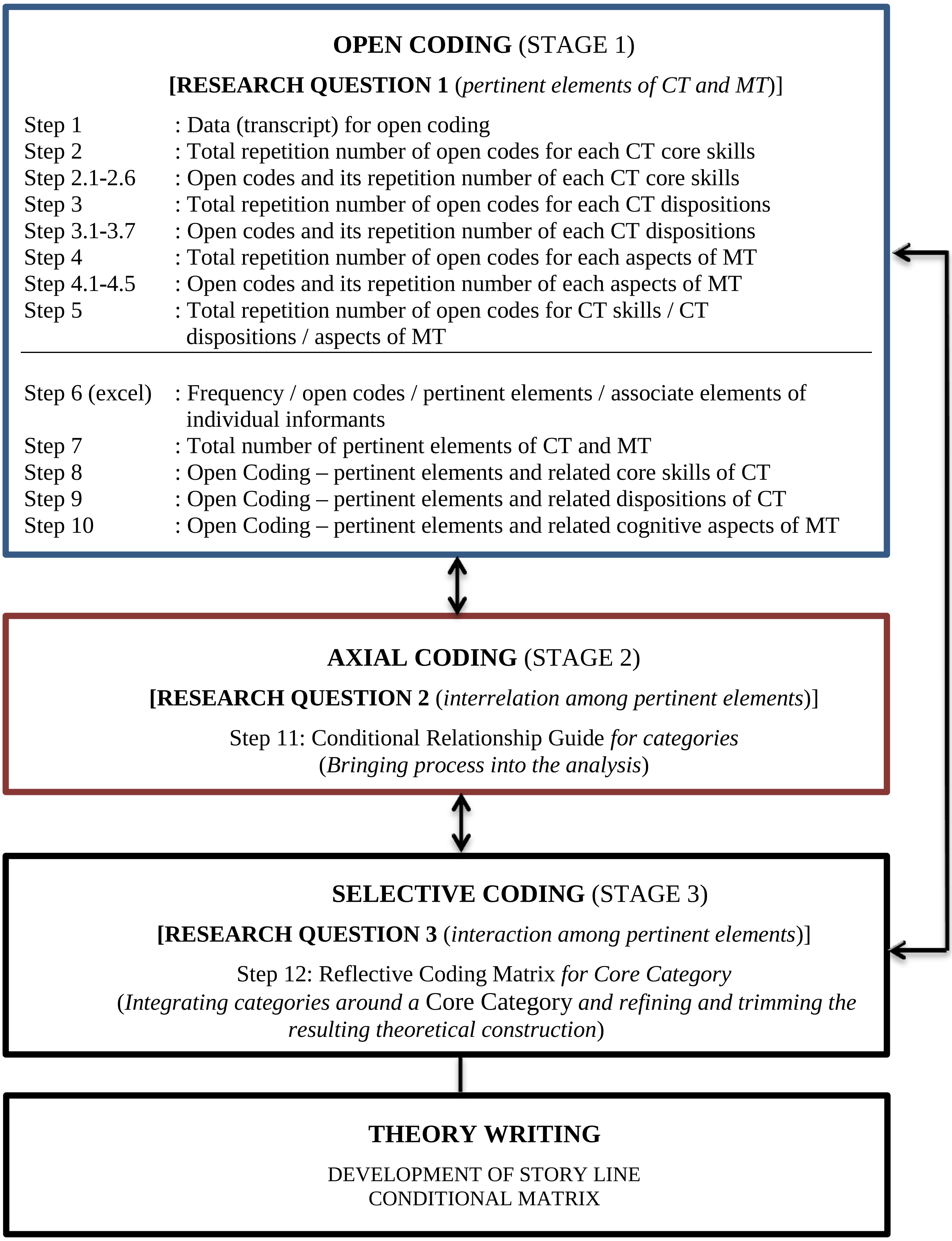


Figure 5.2: Overview of Data Analysis Process

5.2 Constant Comparative Method

Constant comparative method was actively carried out throughout the analysis process, mainly during open and axial coding. As visualized in Figure 3.5 where constant comparison goes hand in hand with theoretical sampling, this section explains how constant comparative method was executed in this study towards the theoretical saturation via theoretical sampling. The constant comparative method is explained in four stages: (1) comparing incidents applicable to each category, (2) integrating categories and their properties, (3) delimited the theory, and (4) writing the theory (Glaser & Strauss, 1967; Glaser, 2008).

The researcher started the analysis by coding each incident into as many categories of analysis as possible. Coding was done by noting categories on margins and eventually tabulated for keeping track of the comparison group for each incident. Along the process, the researcher coded a category several times and started to be musing over theoretical notions. At this point, memo was written to capture the theoretical notions, to reflect and steer thinking to logical conclusions adhering to data.

This iterative process was continuing as theoretical sampling was carried out. The code assigned for each incident was compared to the new data to fit the code or create new emergent codes from the data. This process involved induction and deduction strategies where pragmatism philosophy underlined the process. This iterative process of constant comparison and theoretical sampling were continuing until a saturation level is reached.

According to Glaser (2008), the comparison could be based on memory and there is no need to refer to the actual note on every previous incident for each comparison. In this study, the researcher has tabulated all the codes with the respective informants to ease the comparison process and determine the saturation point. Through the constant comparative method, no more new categories or themes were identified significantly different from the previous emergent categories after the fifth interview. At this point, the saturation level was about to be reached. The researcher decided to stop sampling after the eighth interview.

The constant comparative method was also actively applied during integrating major categories and their properties, involving all emergent pertinent elements of critical thinking and mathematical thinking. The comparison process together with the written memos helped the researcher to establish and develop the interrelation and interaction among these pertinent elements through the research tools used in this study. The Conditional Relationship Guide used during axial coding has established the interrelation among pertinent elements through its relational questions. The Reflective Coding Matrix developed the interaction among pertinent elements to contextualize the central phenomenon.

Delimiting features of constant comparative method helped to manage the overwhelming task for handling about two hundred codes in developing a substantive theory. The comparison method modified and reduced terminology and original list of categories for coding, to become denser and solid. This process continued until theoretical saturation level was reached. An example of code/category reduction is, *relating/identifying relationship* was absorbed into *looking for patterns/relating/working with related problems*.

In this study, the open codes were modified, re-categorized and reduced through comparison method and left only fifty three codes from initially about two hundred codes, and have been known as pertinent elements of critical thinking and mathematical thinking. In writing story line for the emerging substantive theory, the researcher relied tremendously on interview transcripts, coded data and written memos during the comparison process. Information from written memos such as ideas or thoughts captured during data collection and analysis, discussions and reflections furnished the content and interpretation behind the categories for development of the story line.

5.3 Open Coding (Stage 1)

Open coding is one of the three basic analytic processes in grounded theory analysis. Through this coding process, the analysis was aimed to answer to the first research question regarding the pertinent elements of critical thinking and mathematical thinking used in real-world civil engineering practice. Details of the open coding process are explained in the remaining parts of this section.

Analyzing interview transcripts for open coding process was not an easy task. The researcher had to make her thinking flexible in two different forms. The first round of analysis required the researcher to immerse herself into the informants' world to understand about design process. The researcher read again and again the transcripts and then, conceptualized the content that related to the design process into appropriate themes. For the second round, the researcher read again the transcripts thoroughly to capture elements of critical thinking and mathematical thinking used in the real-world practice.

Referring to the data analysis strategies as shown in Figure 5.2, the first step of analyzing data was to code the transcript. The transcripts of the interview were the main data source in this study. The open coding process was initiated on the first transcript as soon as it was transcribed closely after the first interview. Each transcript was coded inductively.

The inductive codes obtained were classified as critical thinking or mathematical thinking, through the lens of Facione for critical thinking and of Schoenfeld for mathematical thinking. Abbreviations for core skills and dispositions of critical thinking and five aspects of cognition of mathematical thinking were assigned for further explanation purposes, as presented in Table 5.1.

Table 5.1: Abbreviations for Critical Thinking and Mathematical Thinking

Types of Thinking		Abbreviation	Meaning
Critical Thinking	Core Skills	CIP	Interpretation
		CAN	Analysis
		CEV	Evaluation
		CIF	Inference
		CEX	Explanation
		CSR	Self-reflection
	Dispositions	CDT	Truth-seeking
		CDM	Open-mindedness
		CDA	Analyticity
		CDO	Orderliness
		CDC	Confidence
		CDI	Inquisitiveness
		CDR	Maturity of judgment
Mathematical Thinking	Aspects of Cognition	MKB	Mathematical knowledge base
		MPS	Problem solving strategies
		MMC	Monitoring and control
		MBA	Beliefs and affects
		MMP	Mathematical Practices

Constant comparison process initiated with the first interview transcript. Comparison was made between data and data, coding and data, coding and coding, with the previous analysed transcripts helps a lot the open coding process. The iterative process of interviewing-coding-comparing-interviewing was continuously carried out, together with theoretical sampling, until reach the sampling saturation and theoretical saturation level. Table 5.2 shows an excerpt of interview transcript with open codes and Table 5.3 shows the open codes with classification of critical thinking and mathematical thinking.

Table 5.2: Interview Transcript with Open Codes

Transcript	Open Codes
Q: What are challenges of software use in designing?	
A: I think you have heard, rubbish in rubbish out... Software facilitates design. Nevertheless, we cannot neglect the code of practice. Even though we have software, we always have to do cross-checking, for example, we do a multi-storey building, we take certain area of the output, we check manually, whether correct or not the calculation done by the computer. We check its compliance to the code of practice, and once satisfied, only then we proceed. It is undoubtedly that using software is very helpful. Now, for multi storey takes within 2 to 3 weeks compared to manual, it took 2 to 3 months. Drafting, drawing, all using auto cad, no more using pen and pencil like before...but then again, when thing becomes easier, we always tend to be negligent, and our negligence makes us forget to see all the miniscule detailing, and this is really alarming and we need to focus on it...	Facilitates designing Code of Practice Conforming Cross-checking Doing calculation Checking manually Conforming Self-regulation Adapting to new approach Concern behaviour
Again, it depends on that particular engineer's expertise and experience. For senior engineers, those who ever did it manually, when it comes to software, they are more meticulous, they know where to check more detail, compared to those young engineers We need to consider safety and also cost implication.	How efficient knowledge/experience is used Checking thoroughly Detecting failure 1) Safety 2) Cost implication
To play safe, most software set its safety factor at high range. Sometimes, when having high safety factor, columns and beams become bigger, in fact, if manually done, they can be smaller, can save cost, and clients also happy can save their money. So, all those things need to be cross checked. Default safety factor usually high, from the layout, we modify where necessary. Definitely the layout outputs need to be checked.	Assessing credibility of output Having mathematical sense making Cross checking Modifying Checking thoroughly

Table 5.3: Open Codes with Classification of CT and MT

Transcript	**Open Codes**	**CT**	**MT**
Q: What are challenges of software usage in designing?			
A: I think you have heard, rubbish in rubbish out... Software facilitates design.	Facilitates designing		
Nevertheless, we cannot neglect the code of practice.	Code of Practice		
Even though we have	Conforming		MMC
software, we always have to do cross-checking, for example, we do a multi-storey building, we take certain area of the	Cross-checking	CSR	
output, we check manually, whether	Doing calculation		MKB
correct or not the calculation done by the computer.	Checking manually	CSR	
We check its compliance to the	Conforming		MMC
code of practice, and once satisfied, only then we proceed.	Self-regulation		MMC
It is undoubtedly that using software is very helpful. Now, for multi storey takes within 2 to 3 weeks compared to manual, it took 2 to 3 months. Drafting, drawing, all using auto cad, no more using pen and pencil like before...	Adapting to new approach		MMC
but then again, when thing becomes easier, we always tend to be negligent, and our negligence makes us forget to see all the miniscule detailing, and this is really alarming and we need to focus on it...	Concern behaviour		MMC
Again, it depends on that particular engineer's expertise and experience.	How efficient knowledge/experience is used		MMC
For senior engineers, those who ever did it manually, when it comes to software, they are more meticulous, they know where to	Checking thoroughly	CAN	
check more detail, compared to those young engineers	Detecting failure	CAN	
We need to consider safety and also cost implication.	3) Safety 4) Cost implication		
To play safe, most software set its safety factor at high range.	Assessing credibility of output	CEV	
Sometimes, when having high safety factor, columns and beams become bigger, in fact, if manually done, they can be smaller, can save cost, and clients also happy can save their money.	Having mathematical sense making		MMP
So, all those things need to be cross checked.	Cross checking	CSR	
Default safety factor usually high, from the layout, we modify where necessary.	Modifying	CSR	
Definitely the layout outputs need to be checked.	Checking thoroughly	CAN	

The subsequent steps of data analysis strategies were to calculate repetition number of open codes related to the critical thinking and mathematical thinking, in order to identify pertinent elements of the both types of thinking. Thus, the third step was to determine the repetition number of open codes for the core skills of critical thinking. See Table 5.4.

Table 5.4: Repetition Number of CT Core Skills of Informant E2

Core Skills of CT	Total Number of Repetition
CIP	2
CAN	6
CEV	2
CIF	8
CEX	1
CSR	8

Then, it was followed by tabulating the open codes with its repetition number for each core skill of critical thinking. The purpose was to itemize all the open codes for each of core skills of the critical thinking. For example, Table 5.5 below shows the repetition number of open codes for analysis (CAN).

Table 5.5: Repetition Number of Open Codes for CAN of Informant E2

Analysis (CAN)	Number of Repetition
Examining ideas	3
Comparing	1
Relating / Identifying relationship	2

The same procedures were applied to the dispositions of critical thinking and aspects of cognition of mathematical thinking, covering all steps from the second until the fourth of the data analysis strategies.

The fifth step was to summarize the total number of open codes for each core skills and dispositions of critical thinking and aspects of cognition of mathematical thinking. See Table 5.6 for the summarization.

Table 5.6: Total Repetition Number of CT Core Skills and Dispositions and MT Aspects of Cognition of Informant E2

CTS, CTD and MTC	Critical Thinking													Mathematical Thinking				
	Core Skills (CTS)						Dispositions (CTD)							Aspects of Cognition (MTC)				
	CIP	CAN	CEV	CIF	CEX	CSR	CDT	CDM	CDA	CDO	CDC	CDI	CDR	MKB	MPS	MMC	MBA	MMP
Total number of repetition	2	6	2	8	1	8	4	0	1	4	4	3	3	12	5	16	2	7

This method covering steps from the first until the fifth was applied as a whole to each interview transcript of individual informants. All the open codes were categorized into two, either as major open code or category. Major open code is open code that represents a collective meaning of the code from informants. Category is an abstraction of few related open codes. Subsequently, all the open codes were listed down to identify pertinent elements of critical thinking and mathematical thinking, as well as associate elements, which are meant for design process.

Therefore, for the sixth step of data analysis strategies, the researcher listed down the open codes from the interview transcripts using Microsoft Excel. In doing this, the results obtained from the earlier steps of data analysis strategies were employed. The Microsoft Excel file listed the informants and frequency of the open codes emerged from the previous steps of data analysis. Table 5.7 is tabulated for showing frequency for open codes of core skills of critical thinking of individual informants. For that purpose, information from Table 5.4, Table 5.5 and Table 5.6 for each open code was applied.

Table 5.7: Frequency for Open Codes of CT Core Skills of Individual Informants

CRITICAL THINKING		INDIVIDUAL INOFRMANTS							
CORE SKILLS	**OPEN CODES**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
Interpretation (CIP)	Categorizing	1	0	0	0	0	0	0	0
	Comprehending & clarify meaning	3	2	2	0	3	1	0	4
	Translating	0	0	0	0	1	0	0	0
	Interpreting	0	0	0	0	1	0	0	0
Analysis (CAN)	Examining ideas/output	5	3	2	1	1	0	0	1
	Reviewing input data /design	1	0	0	0	0	0	3	2
	Comparing	0	1	3	0	0	0	0	0
	Relating/identifying relationship	4	2	4	0	0	0	1	4
	Checking thoroughly	0	0	1	0	1	1	3	1
	Detecting failure	0	0	1	0	0	0	2	1
Evaluation (CEV)	Assessing credibility of output / info	7	2	2	2	1	1	1	3
	Drawing conclusion	1	0	0	0	0	0	0	0
	Revising /reanalyse design	0	0	0	0	2	2	2	3
Inference (CIF)	Considering relevant info	4	2	2	2	1	1	3	7
	Drawing reasonable conclusion	3	0	1	0	0	0	0	3
	Seeking for relevant info.	0	1	0	0	0	5	2	4
	Forming conjectures	2	5	5	0	4	2	1	3
	Inference	0	0	1	0	0	0	0	0
	Gathering / collecting relevant info	0	0	0	0	0	2	0	3
Explanation (CEX)	Justifying reasonably	2	0	2	0	1	1	5	0
	presenting well-reasoned argument	0	1	0	0	0	0	0	0
	Defending with good reasons	1	0	0	0	1	0	0	3
Self-reflection (CSR)	Counter -checking	1	3	2	0	6	7	4	2
	Correcting /self-correction	1	3	0	0	2	1	0	2
	Confirming	2	2	2	0	4	1	2	4
	Self-consciousness	0	0	1	1	1	0	3	2
	Complying	0	0	1	3	1	1	1	2
	Adjusting	0	0	0	1	0	0	1	0
	Validating	0	0	0	0	1	0	0	0
	Amending	0	0	0	0	0	1	1	2
	Verifying	0	0	0	0	0	2	0	0
	Modifying	0	0	0	0	0	0	1	0

The best verbatim excerpts from transcripts that give meaning to the open codes

In the table, the researcher also highlighted the box where to keep track of the best verbatim excerpts from interview transcripts. It was for the contented feeling when the excerpts give meaning to the open codes or answering the research questions in exactly the right way. The researcher then used the excerpts as support in the development of story line of the emerging theory during the selective coding process. The same step was applied for the tabulation of open codes for the dispositions of critical thinking, as shown in Table 5.8 and also for the aspects of cognition of mathematical thinking, as shown in Table 5.9.

Table 5.8: Frequency for Open Codes of CT Dispositions of Individual Informants

CRITICAL THINKING		INDIVIDUAL INFORMANTS							
DISPOSITIONS	**OPEN CODES**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
Truth seeking (CDT)	Flexibility in considering alternatives	1	4	4	2	1	1	1	0
	Seeking the best info	0	0	1	1	0	0	1	1
Open Mindedness (CDM)	Understanding others' opinions	4	0	0	0	1	0	0	0
	Tolerant of divergent views	0	0	1	2	1	0	6	1
Analyticity (CDA)	Anticipating the results	0	1	0	0	0	0	1	2
	Using evident to resolve problem	0	0	0	0	1	0	1	1
Orderliness (CDO)	Diligence in seeking info	4	4	2	1	0	1	2	0
	Systematic/organized	0	0	1	0	1	0	1	0
Confidence (CDC)	Confidence in reasoning	4	4	0	0	1	2	5	4
Inquisitiveness (CDI)	Intellectual curiosity	0	2	2	0	1	1	2	1
	Staying well-informed	1	1	0	0	0	0	1	0
Maturity (CDR)	Careful and prudent	3	3	2	2	0	1	3	0

The best verbatim excerpts from transcripts that give meaning to the open codes

Table 5.9: Frequency for Open Codes of MT Aspects of Cognition of Individual Informants

MATHEMATICAL THINKING		INDIVIDUAL INFORMANTS							
ASPECTS OF COGNITION	**OPEN CODES**	**E1**	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**
Knowledge Base / Cognitive Resources (MKB)	Informal knowledge/ intuitive knowledge	2	0	0	0	1	1	0	0
	Using algorithmic	3	10	0	0	0	0	0	0
	Calculating/measuring	3	2	0	1	1	2	2	3
	Engineering sense	1	0	0	0	0	1	0	2
	Applying/transferring maths knowledge / theory	0	0	3	0	0	0	1	2
	Using standard equation/formula	0	0	1	1	0	0	2	3
	Estimating	0	0	0	1	0	1	0	0
	Common sense	0	0	0	0	0	0	1	0
Problem Solving Strategies / Heuristics (MPS)	Looking for patterns	2	1	1	0	0	0	1	1
	Working backwards	1	1	1	0	2	0	1	0
	Decompose & recombine	1	0	0	0	0	0	0	0
	Doing routine practice	1	0	0	0	0	2	0	0
	Working rote exercise	1	0	0	0	0	0	0	0
	Analytical reasoning skill	0	1	1	0	0	0	1	0
	Simulate real life exp.	0	2	1	0	2	0	0	0
	Seeking relevant info	1	0	0	0	0	0	1	0
	Attending to problem	1	0	0	0	0	0	0	0
	Making/exploit analogies	0	0	2	0	0	0	0	0
	Working with related problems	0	0	0	1	0	0	1	1
	Higher level skills to solve non routine	0	0	0	1	0	0	0	0
	Arguing with contradiction	0	0	0	0	1	0	0	0
	Solving open-ended problems	1	0	0	0	2	0	0	1
	Drawing / sketching/scanning	0	0	0	0	0	1	1	5
	Modelling design	0	0	0	0	0	0	0	1
	Gathering info / data	0	0	0	0	0	1	0	3
Monitoring and Control (MMC)	Selecting/pursuing the right approach	9	7	4	4	5	2	11	9
	Concern behaviours	9	4	2	4	5	0	8	2
	Making plans	1	0	0	1	0	0	0	0
	Having discussion	6	3	1	2	0	2	4	3
	Applying suggestion	1	0	0	0	0	0	1	0
	Self-regulation	2	0	0	2	1	1	7	3
	Decision to be made along the way	1	2	0	1	0	0	3	0
	Conforming	0	0	0	5	1	3	3	0
	How efficient knowledge/experience is used	0	0	0	0	1	0	8	4
	Adapting new/different approach/situation/experience	0	0	0	0	5	0	6	1
	Brainstorming	0	0	0	0	0	0	1	0
Belief and Affect (MBA)	Dominating orientation	0	1	0	0	0	0	6	2
	Giving alternative solutions / ways	0	1	3	2	2	0	1	1
	Maths consciousness/consciousness in assessing material	0	0	3	1	4	0	0	2
	Mathematical proficiency	0	0	0	1	2	0	1	0
Mathematical Practices (MMP)	Having mathematical sense-making	3	2	2	1	1	0	3	1
	Forming conjectures / assumption	2	2	5	1	3	2	0	1
	Manipulating formula/data/symbols/equation	1	1	3	1	0	0	0	1
	Defending claims mathematically	2	0	1	1	1	0	1	1
	Having mathematical points of view	1	1	0	3	1	0	1	2
	Coming to grip with uncertainties	2	1	2	1	3	0	1	1

The best verbatim excerpts from transcripts that give meaning to the open codes

The pertinent elements consist of selected major open codes and categories, while associate elements are major open codes and categories other than pertinent elements. The pertinent elements were identified according to the predominant pattern and frequency in the listing. As a basis of the identifying process, the researcher has set minimum criteria for the selection. For the predominant pattern, number of informants who mentioned the open code must be more than one. Whereas for the frequency, number of repetition for the open code that being mentioned must not less than three times. These criteria were set for minding such big pool of data after considering the prevailing pattern and frequency of overall data.

Based on the selection criteria, a total of sixty five major open codes and categories were selected as predetermined pertinent elements from about two hundreds open codes during the open coding process. These sixty five major open codes and categories were then refined and abstracted to be categorized as major categories. As a result, a total of fifty three major categories emerged and were determined as pertinent elements of critical thinking and mathematical thinking. These pertinent elements of critical thinking and mathematical thinking are mainly used in the real-world civil engineering practice. Subsequently, the major categories identified as pertinent elements were reviewed and verified by experts in those particular fields to ensure trustworthiness.

For each pertinent element, the best verbatim excerpt selected among the informants as indicated in Table 5.7, Table 5.8 and Table 5.9, gives meaning and relevance in this study. Table 10 lists all fifty three of the pertinent elements and their meanings through the best verbatim excerpts identified from this study.

Table 5.10: Pertinent Elements and Meanings

Pertinent Elements	**Meanings (the best verbatim excerpts)**
Adapting new/different approach/situation/experience	The longer he involves in a field, the more experience he gains, which can be adapted to the next projects
Amending	So, we will gather all the comments from each department and based on the comments, we will amend the layout.
Analytical reasoning skills	Sometimes if we change the layout, infra will be affected, especially its flow path. For example, if having two pipe lines of water and sewer, plus with drainage, concerning about their flow paths, we have to find out, which one is lower than the other, and also the drainage
Anticipating the results	Concept layout is very important, once we got it correct, if we enter it into software, sure it will be fine and got no problem.
Applying / transferring maths knowledge / theory	Software is indeed a need; nevertheless, knowledge and theory we learnt during our study in university is also actually being applied, as it is being used in the software in the simplified form. So, the software just facilitates our job.
Assessing credibility of output/info	Before producing the drawing, we will go through the output again, for both structure and infra, at least we go through again to check whether ok or not, then only we proceed
Careful and prudent	…after that we will discuss with the boss, and if he also agrees, we will submit our view to the authorities and if it is rejected, then only we will submit the one that using computer.
Checking thoroughly	Depends on their confidence, sometimes they come and seek for some advices, but I ask them to sit down together and check thoroughly the design concept as I am more satisfied to supervise from the beginning and not only at the end of the project
Clarify meaning	At preliminary stage, after getting the architecture drawing, we have to study it and determine our layout structure
Coming to grip with uncertainties	…for SAJ, water supply and sewerage, it is challenging when having unexpected problem, such as blocking the existing pipe, so, we have to think of how to solve the problem, how to lay the pipe in order to have a good flow and we have to make suggestions
Complying	As long as we follow the specification, it means we are fulfilling their needs. If what we do is within specification, complete with its protection, we are freely to design without any problem.
Comprehending	When we want to design, we must aware of all the changes, and to understand the meaning of the changes
Concern behaviour in making decision	It is undoubtedly that using software is very helpful…..but then again, when thing becomes easier, we always tend to be negligent, and our negligence makes us forget to see all the miniscule detailing, and this is really alarming and we need to focus on it
Confidence in reasoning	We cannot neglect safety factors and related specifications in satisfying something, and at the same time, we must confident that the thing we are going to do is workable, and having confidence in our design.
Confirming	There was a case, where, after the building was built, they found some cracks. We rechecking our design, running into software, and it was confirmed our mistake. We had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks.
Conforming	…also have its specifications in the BQ, as well as in the drawing. Meaning, it's within the specifications and does not deviate from what has been submitted.
Considering relevant info	Design is design, need is need, meaning, if client wants to save cost, we can consider the minimum design but still having buffer for safety factors
Correcting / Self-correction	After calculating the water demand, we do design, and after designing, if realized that we have over designed it, we can reduce the size from the result obtained using software.
Counter checking	Software is used for doing calculation but for simple calculation we do it manually. We counter-check its output and make adjustment according to the specification. Thus, mathematical thinking is important in designing.

Table 5.10: Pertinent Elements and Meanings - continue

Pertinent Elements	**Meanings (the best verbatim excerpts)**
Decision to be made along the way	Our concerns continue until all work at site is finished, and it's not only revising documentation, sometimes after tendering out, still have amendments to be done
Defending claims mathematically	We cannot compromise on safety to save cost, we have our permissible limit, if the size of the beam really cannot be reduced, we have to defend it, and as an engineer, we indeed have to defend it.
Defending with good reason	…for gaining experience, it takes some time, it is there but we have to find the data, and the data must be correct, our assumption also must be correct, then only our design will be correct, and even later if it fails, it is not our faults but might be because of something else.
Detecting failure	For senior engineers, those who ever did it manually, when it comes to software, they are more meticulous, they know where to check more detail, compared to those young engineers
Diligence in seeking info	Sometimes asking the local people or the authorities about any new development there, if any, and the contractor also sometimes gives some info..
Dominating orientation	…it does not involve the whole design, we will try our best to minimize the cost, and at the same time to make it workable
Drawing reasonable conclusion	For example, for installing a culvert at the place where the ground is not so strong, is it necessary to do piling for its foundation? After having discussion, we decided not to do it to let the culvert settle with minimum rate, because piling without doing grounding treatment for the road will make the culvert bulging and this will cause problem to the road users
Engineering sense	If we are designing a building, where to put its beams and columns, where are the best position for them, and at the same time we want to minimize the columns because we want to minimize its foundation. So, all this comes from our sense, our creativity
Examining Ideas / output	Usually, from the architecture drawing, we could see where the beam, column and slab are placed, and if the columns are having too big gap, we will ask permission from the architect to add some more columns, or otherwise the beam will be bigger.
Flexibility in considering alternatives	Sometimes what we design does not totally fit the real situation at site, or maybe difficult to execute, so, we have to think of other alternatives.
Forming conjectures / assumption	For structure, we just enter into the software, but if it fails, we have to find out possible reason, maybe we have put too much loading, or have mistakenly doubled it, or maybe entered without loading, and one more thing, to look at its support direction, which all these could be factors of failure of a design for certain beams, slabs or columns.
Gathering info / data/relevant info	Either directly under contractor, architect or developer, the flow of work remains the same, meaning, we know our scope of work and we will gather information...if we got comments from the authorities, such as, have to widen the drain or insufficient pond, then, we gather all the comments and forward to planner
Giving alternative ways / solutions	Usually we have to check it one by one, perhaps, some of the things we apply to the drawing is unnecessary, and maybe we can do it another way
Having discussion	…we have to know all, cannot miss any data, and must have sufficient data, and all this is done in a team, having discussion, again and again….
Having mathematical views and sense-making	Sometimes, when having high safety factor, columns and beams become bigger, in fact, if manually done, they can be smaller, can save cost, and clients also happy can save their money. We follow a rule of thumb, if for column will be 6%, and if for IWK, usually will be based on unit, but, if we based on area, we already have our own table, so, we can estimate it
How efficient knowledge / experience is used	We do not come with unattended problem, we must act fast, meaning, we use our experience and knowledge to solve the problem
Informal knowledge / Intuition / imagining	Those skills come by experience, not stated in books….it is more to our experience, and experience teaches us a lot…
Intellectual curiosity	We have to know their needs, let say we build a road, how much depth is required, what is the purpose of building this road, or maybe we have to collect some data that is called traffic impact assessment to determine how many lanes are appropriate for the road.

Table 5.10: Pertinent Elements and Meanings - continue

Pertinent Elements	**Meanings (the best verbatim excerpts)**
Justifying reasonably	As an engineer, he must be able to justify his design. If he says four pillars are sufficient for supporting the loading, and if he can justify it and prove it with code of practice, then, go ahead.
Looking for patterns	Having good rapport and experience is priceless, they can be adapted in other projects, but for layout, definitely different as it cannot be reused, except for schools that following JKR standards
Manipulating formula / input data/symbols/ equation	Sometimes we cannot get the answer from the software, so, we have to manipulate an equation to get another calculation
Mathematical proficiency	All stages involve mathematics, not so much at the input data, but, other than that, all involves mathematics
Maths consciousness/ consciousness in assessing material	All stages involve mathematics, not so much at the input data, but, other than that, all involves mathematics
Revising / reanalyse design	….when we produce our output, it will be commented by several parties, then, we have to revise accordingly
Selecting / Pursuing the right approach	If we want to get an info in structure, we use the right formula and it is being well followed, but, how we approach our clients, it depends on individual skills to accelerate the process
Self-consciousness	Sometimes we mistakenly typed it and then passed to draftsman, I have read a saying " there is no such thing as simple mistake for civil engineer' and until now I do remember it, so, to best possible, we have to minimize all the simple mistakes before producing the drawing
Self-regulation	Some of the clients, even though we have not got approval of the submission, they insist to proceed. We can only agree with them with condition that if later, there are any comments from authority, we have to follow and if they agree, then only we proceed.
Simulate real life experience	…and for this, experience is helpful because we have to think of how will they execute it later, especially the contractor, if we do like this, how well can they do it?
Solving open-ended questions	When we investigated the soil, all was fine and we determined the place to do piling. But then, when they were doing the piling, the piling was broken, again and again, so, since we were facing the problem during that time, we had to make fast decision on what to do now, how to do…
Tolerant of divergent views	At the beginning stage, we have to confirm with client about the need statement, let say the owner wants to develop a bungalow, today he comes with this idea, so, we workout based on his idea, later, when we meet again, he has other different idea, so, this stage usually takes long time
Understanding others' opinions	So far, I have never seen exactly the same approach been applied to different work, different clients have different ways and needs, so, we have to act accordingly, as long as it does not against our work ethic as an engineer.
Using evident to resolve problems	We had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks. We panicked, at that time we had no professional engineer but only a supervisor, so, we sat down and discussed on what had happened and how to rectify it.
Using standard equation/formula/algorithm	Actually, indirectly, we use what we learnt, like calculus, and even though it is not directly applied, it is embedded in the formulae that we use for doing calculation.
Working backward	Our input determines our product, if we find some peculiar things at our product, we have to re-check its basic input data in computer, and this part requires manual knowledge

After the process of identifying pertinent elements completed, the seventh step of data analysis strategies was carried out. It was to determine number of pertinent elements for each core skills and dispositions of critical thinking and aspects of cognition of mathematical thinking, as have been identified in the previous step of analysis.

For that, Table 5.11 shows the total number of pertinent elements for the core skills and dispositions of critical thinking, as well as for the aspects of cognition of mathematical thinking. In this table, another three abbreviations were used such as CTS to represent the core skills of critical thinking, CTD for the dispositions of critical thinking and MTC for the aspects of cognition of mathematical thinking. The total number of pertinent elements of critical thinking was a sum of the number of pertinent elements of each core skills and dispositions of critical thinking. For mathematical thinking, the total number of pertinent elements was a sum of the number of pertinent elements of each aspects of cognition of mathematical thinking.

Table 5.11: Total Number of Pertinent Elements for CT Core Skills and Dispositions and MT Aspects of Cognition

CTS, CTD and MTC	Critical Thinking													Mathematical Thinking				
	Core Skills (CTS)						Dispositions (CTD)							Aspects of Cognition (MTC)				
	CIP	CAN	CEV	CIF	CEX	CSR	CDT	CDM	CDA	CDO	CDC	CDI	CDR	MKB	MPS	MMC	MBA	MMP
Number of pertinent elements	2	3	2	2	2	6	1	2	2	1	1	1	1	4	6	8	4	5
Total number of pertinent elements	**17**						**9**							**27**				

The table shows there are seventeen pertinent elements for core skills of critical thinking, nine pertinent elements for disposition of critical thinking and twenty seven pertinent elements of aspects of cognition of mathematical thinking. The sum of pertinent elements of critical thinking is twenty six, which is about the same figure with number of pertinent elements of mathematical thinking.

The next step in data analysis process is to list down all the pertinent elements according to the number of pertinent elements mentioned in the Table 5.11. Thus, the pertinent elements for the related core skills of critical thinking are shown in Table 5.12 below. Similarly, Table 5.13 shows the pertinent elements for the related dispositions of critical thinking. The pertinent elements for the related aspects of cognition of mathematical thinking are shown in Table 5.14.

Table 5.12: Pertinent Elements and Related Core Skills of CT

Pertinent Elements (Major Open Codes/ Categories)	Core Skills of Critical Thinking
Comprehending	Interpretation (CIP)
Clarifying meaning	
Examining Ideas/output	Analysis (CAN)
Checking thoroughly	
Detecting failure	
Assessing credibility of output/info	Evaluation (CEV)
Revising/Reanalyse design	
Considering relevant info	Inference (CIF)
Drawing reasonable conclusion	
Justifying reasonably	Explanation (CEX)
Defending with good reasons	
Counter checking	Self-reflection (CSR)
Correcting/Self correction	
Confirming	
Self-consciousness	
Complying	
Amending	

Table 5.13: Pertinent Elements and Related Dispositions of CT

Pertinent Elements (Major Open Codes/ Categories)	Dispositions of Critical Thinking
Flexibility in considering alternatives	Truth-seeking (CDT)
Understanding others' opinions	Open-mindedness (CDM)
Tolerance of divergent views	
Anticipating the results	Analyticity (CDA)
Using evident to solve problems	
Diligence in seeking info	Orderliness (CDO)
Confidence in reasoning	Confidence (CDC)
Intellectual curiosity	Inquisitiveness (CDI)
Careful and prudent	Maturity (CDR)

Table 5.14: Pertinent Elements and Related Aspects of Cognition of MT

Pertinent Elements (Major Open Codes/ Categories)	Aspects of Cognition of Mathematical Thinking
Informal knowledge/Intuition/imagining	Cognitive mathematical knowledge base (MKB)
Engineering sense	
Applying/transferring maths knowledge/theory	
Using standard equation/formula/algorithm	
Looking for patterns	Problem solving strategies / heuristics (MPS)
Working backward	
Analytical reasoning skills	
Simulate real life experience	
Solving open-ended questions	
Gathering info/data/relevant info	
Selecting /Pursuing the right approach	Monitoring and control (MMC)
Concern behaviour in making decision	
Having discussion	
Self-regulation	
Decision to be made along the way	
Conforming	
How efficient knowledge/experience is used	
Adapting new/different approach/situation / experience	
Dominating orientation	Belief and affects (MBA)
Giving alternative ways/solutions	
Maths consciousness/consciousness in assessing material	
Mathematical proficiency	
Having mathematical views and sense-making	Mathematical practices (MMP)
Forming conjectures/assumption	
Manipulating formula/input data/symbols/ equation	
Defending claims mathematically	
Coming to grip with uncertainties	

These groupings are treated as the main reference for the next stage of data analysis. Subsequently, the groupings are extended as the analysis progress that provide the foundation to the logic diagrams done during the axial coding (Strauss & Corbin, 1998). For that purpose, the Conditional Relationship Guide is used during the axial coding process.

5.4 Axial Coding (Stage 2)

Axial coding is the second coding process of the three basic analytic processes in grounded theory analysis. Outcomes of the axial coding was sought to answer the second research question of this study regarding the interrelation among the pertinent elements of critical thinking and mathematical thinking during the execution of the engineering design process.

Each of the fifty three major categories identified as the pertinent elements was explained in depth in axial coding process. In this axial coding process, the researcher concentrated on relating and understanding the interrelation among the pertinent elements. Thus, the interrelation between categories was developed by answering the questions, what, where, when, why, how and with what consequences. The process was visualized through the analytic tool, Conditional Relationship Guide. All the fifty three pertinent elements were explained and arranged alphabetically in the Conditional Relationship Guide. Table 5.15 shows samples of this process for several pertinent elements such as adapting new/different approach/situation/experience, amending, analytical reasoning skills and anticipating the results. The other pertinent elements which were also explained through the Conditional Relationship Guide are shown in Appendix E. Codes are italicized and used to define each category relatively. The Conditional Relationship Guide is utilized to clarify the process. It contextualizes the central phenomenon and relates categories structure with process, which specifically engages Strauss and Corbin's relational investigative questions (Scott & Howell, 2008).

Table 5.15: Conditional Relationship Guide

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Adapting new/different approach/situation/experience	The longer he involves in a field, the more experience he gains, which can be adapted to the next projects	Design stage; Preliminary stage	Monitoring and Control	Giving alternative ways;	Justifying; Conforming; Having discussion	Self-regulation; Selecting/pursuing the right approach; How efficient knowledge / experience is used
Amending	So, we will gather all the comments from each department and based on the comments, we will amend the layout.	Design stage	Self-reflection	Revising;	Gathering relevant info; Cross checking; Checking thoroughly	Decision to be made along the way; Tolerant to divergent views
Analytical reasoning skills	Sometimes if we change the layout, infra will be affected, especially its flow path. For example, if having two pipe lines of water and sewer, plus with drainage, concerning about their flow paths, we have to find out, which one is lower than the other, and also the drainage	Design stage	Heuristics	Coming to grips with uncertainties; Making conjectures;	Simulate real life experience; Identifying relationship; Working backward	Justifying; How efficient experience is used; Revising
Anticipating the results	Concept layout is very important, once we got it correct, if we enter it into software, sure it will be fine and got no problem.	Preliminary stage; Design stage	Analyticity	Dominating orientation	Tolerant of divergent views; Making conjectures; Having mathematical views and sense making; Engineering sense	Confidence in reasoning; Defending with good reason

The Conditional Relationship Guide also helped the researcher to understand the dynamic interactions among the pertinent elements by asking why and how questions that giving ideas of dynamic process over time. Although the study reports record in time, the informants continue to interact with realities (Scott & Howell, 2008) and this dynamic interaction is known as process (Strauss & Corbin, 1998). Thus, the relational questions provide insights in leading the researcher to the informant's mode of understanding the consequences. These consequences are the key categories where all other categories are focused.

As a result, the interrelation among the pertinent elements is identified. The consequences are the group that is primarily focused on, during the selective coding stage. That analytic tool consists of six columns; category, what, where, when, why, how and consequence, and is formatted to ask and answer each relational question about the category named in the far left column. Explanation and example of each relational question are as follows:

What is [the category]? It is content determination. It is defined either by using collective definitions based on codes or using the words of informant(s) that seems to capture the collective meaning of the category. Mostly, in this study, the researcher prefers to use the words of informants to avoid bias. For example, for the category named 'adapting new approach / experience', the researcher used quotation from the informant to answer it: '*The longer he involves in a field, the more experience he gains, which can be adapted to the next projects'*

Where / When does [the category] occur? In this context of study, for 'Where' question is answered using 'in': in the design stage, in the preliminary stage. Whereas for 'When' question is answered using 'during': during analysing, during explaining, during making inference. To conclude, the researcher has chosen to be more specific in answering 'when' question and to answer more broadly in 'where' question. For instance, where and when do the 'adapting new approach / experience' occur? The answers are *'in the stage of design and construction', during 'monitoring and control'.*

Why does [the category] occur? To answer this question, the researcher chooses the related pertinent elements for the particular category. The selected major open codes or categories, those giving overarching meaning of purposes, are chosen for answering this question. For instance, why does 'adapting new approach / experience' occur? The answer is *because of giving alternative ways.* Every project design is unique with a different set of goals and constraints.

Each project is unique, in the sense that each project has its own different problem and challenge. (E7)

However, experience of approaching problems along the project could be adapted to another design project. By applying this experience into other project would give alternative ways and perspectives in handling and solving problems.

The longer he involves in a field, the more experience he gains, which can be adapted to the next projects. (E7)

How does [the category] occur? This question is showing action/interaction among the pertinent elements of that particular category. It brings the idea of dynamic process over time into the analysis. It gives great influence in determining the informant's mode of understanding the consequences. For this, the researcher chooses the related pertinent elements for the particular category, those offering more to the meaning of processes. For instance, how does 'adapting new approach / experience' occur? *By justifying, conforming, and having discussion.*

With what consequence does [the category] occur or is [the category] understood? The consequence is the meaning the informants get purposely and intentionally, such as experience and the right approach. For this example of category, 'adapting new approach / experience', its consequences are *self-regulation, selecting/pursuing the right approach, and how efficient knowledge / experience is used.*

Through this process of axial coding, the researcher completed the Conditional Relationship Guide with all the fifty three pertinent elements. Together with the information extracted from Table 5.11 which showing about the same total number of pertinent elements, the interrelationship between critical thinking and mathematical thinking was developed. Accordingly, this finding served the answer for the second research question about the interrelation among pertinent elements. It suggests that in the design process, both critical thinking and mathematical thinking were equally important in the sense of:

i. Both critical thinking and mathematical thinking were interwoven
ii. Both critical thinking and mathematical thinking were concurrently used
iii. Both critical thinking and mathematical thinking were indispensable
iv. Both critical thinking and mathematical thinking were inexorably linked

Those suggestions are supported by the quotes below:

In designing, CT and MT are surely combined because both are concurrently used. So, it is good if can be applied to students, this understanding of CT and MT, because maybe basic knowledge can be given, like how to tackle a problem of a case, including communication……CT and MT run concurrently, we use both thinking in designing… (E3)(Interwoven; concurrently used)

When we cannot get the answer from software, we have to manipulate the equation for getting another calculation. For obtaining that formula or the way to solve the problem, we have to apply a method or a skill, and CT is the thing that we have to have. It means, we use CT to think of how to manipulate the mathematical formula itself. (E3)(Indispensable)

Sometimes what we do, not saying it is wrong, but, construction-wise, it is difficult to be done. So, we have to think of other alternative to be done. Meaning, we use CT to think of other alternative or to set tolerance to our design. (E3)(Indispensable)

CT is predominantly used at the early stage of designing, and then, we use all the sources we have to smoothen our design work….both CT and MT are used, cannot stop just like that, they are indeed combined together…(E4)(Inexorably linked; interwoven; concurrently used)

Therefore, using the Conditional Relationship Guide in the axial coding process helped the research to visualize the interrelation among the pertinent elements, and to understand how the consequences of each pertinent element are understood. Looking at the Consequences column, there were thirty six pertinent elements listed. Those pertinent elements appeared as consequences for more than once, were selected as major consequences. The other pertinent elements were reserved to be potentially positioned as dimensions in the Reflective Coding Matrix, which was used during selective coding. After excluding the set-aside pertinent elements, there were left twenty four major consequences, as shown in Table 5.16. These major consequences play an important role in developing the Reflective Coding Matrix.

5.5 Selective Coding (Stage 3)

Selective coding is the third coding process in grounded theory analysis, refers to the integration of the major categories in developing an emerging substantive theory from the data. It explains the interaction among pertinent elements of critical thinking and mathematical thinking through the development of story line which is answering the third research question of this study.

From the interrelation among the pertinent elements established by the Conditional Relationship Guide in axial coding process, the consequences are identified as the key category about which all other categories are focused. There were twenty four major consequences appeared as shown in Table 5.16. These major consequences become the main contributor to the development of Core Category.

Table 5.16: Pertinent Elements Identified as Major Consequences

Major Consequences
Careful and prudent
Complying (verifying/validating)
Concern behaviour in making decision
Confidence in reasoning
Self-correction
Decision to be made along the way
Defending claims mathematically
Defending with good reasons
Diligence in seeking info
Dominating orientation
Drawing reasonable conclusion
Engineering sense
Flexibility in considering alternatives
Forming conjectures / assumption
Giving alternative ways / solutions
Having mathematical views and sense-making
How efficient knowledge / experience is used
Justifying reasonably
Mathematical proficiency
Maths consciousness/ consciousness in assessing material
Selecting / Pursuing the right approach
Self-consciousness
Self-regulation
Tolerant of divergent views

Table 5.17 shows the Reflective Coding Matrix which was used to weave the data together in connection with results from the Conditional Relationship Guide. The main objective of constructing the Reflective Coding Matrix is to develop the Core Category, the central phenomenon of the study about which other categories relate. The Core Category can be described in terms of its properties, processes, dimensions, contexts, and the modes with which its consequences are understood. Once the Core Category is determined, all other categories become sub-categories.

There are many possible approaches to developing the Core Category. The researcher chose to begin constructing the Reflective Coding Matrix by identifying the *processes*, followed by determining the *contexts*, *dimensions*, *modes for understanding the consequences*, forming educated guess on *Core Category*, and finally, identifying the *properties*. This process is not a rigid linear process as it is continually back and forth to the open coding, the data and the literature along the process, in ensuring its credibility. Strauss and Corbin (1998) envision placing categories during axial coding process like to fit the pieces of the data puzzle together. An analyst becomes more theoretically sensitive to fit and make sense the categories after several attempts of trial and error. Similarly, Scott (2004) analogizes the process of identifying the Reflective Coding Matrix descriptors like completing a jigsaw puzzle, trying a piece at a time until it all fits and makes sense. Details of the process are discussed below for each descriptors mentioned on the Reflective Coding Matrix.

Processes were identified among the major consequences. Initially, nine out of twenty four major consequences were selected as possible processes. The selection was made by choosing which major consequences are gerunds that having progressive or continuous verb tenses. From there, the selection was refined and six processes were eventually identified: Complying Requirements, Defending Claims with Good Reasons, Drawing Reasonable Conclusion, Forming Conjectures/ Assumption, Giving Alternative Ways/Solutions, and Selecting/Pursuing the Right Approach. Again, it is important to mention that it was not a rigid linear process or a specific formulaic procedure in doing any selection along the process of constructing the Reflective Coding Matrix. There are many possible approaches in determining

Table 5.17: Reflective Coding Matrix

Core Category	**Justifying Decision Reasonably in Dominating Orientation**					
Processes (action/interaction)	Complying requirements	Forming conjectures / assumptions	Drawing reasonable conclusion	Defending claims with good reasons	Giving alternative ways / solutions	Selecting / Pursuing the right approach
Properties (characteristic of category)	Self-consciousness	Adeptness	Anticipation	Justification	Perception	Adaptation
Dimensions (property location on continuum)	▪ Conforming ▪ Gathering relevant info ▪ Confirming ▪ Self-correction ▪ Self-regulation ▪ Mathematical consciousness ▪ Counter checking ▪ Revising ▪ Amending	▪ Analytical reasoning skills ▪ Simulate real life experience ▪ Mathematical views and sense-making ▪ Informal knowledge /Intuition /imagining ▪ Understanding others' opinions	▪ Comprehending ▪ Clarify meaning ▪ Examining ideas ▪ Assessing credibility of statement ▪ Having discussion ▪ Looking for patterns ▪ Using evidence to resolve problems	▪ Solving open ended questions ▪ Detecting failure ▪ Engineering sense ▪ Defending claims mathematically ▪ Considering relevant info ▪ Working backward	▪ Checking thoroughly ▪ Diligent in seeking info ▪ Intellectual curiosity ▪ Coming to grips with uncertainty	▪ Applying theory /knowledge ▪ Adapting experience, new/ different approach ▪ Manipulating formula/equations ▪ Using standard formula/equations
Contexts	Self-reflection	Proficiency	Inference	Explanation	Belief and affect	Monitoring and control
Modes for understanding the consequences (process outcome)	Careful and prudent	Tolerant of divergent views	Concern behaviour	Confidence in reasoning	Flexibility in considering alternative	How efficient knowledge / experience is used

criteria for the selections. Therefore, memos written during axial coding capturing all the thought process along the analysis is important and invaluable (Scott, 2002; Strauss & Corbin, 1998). The written memos helped the researcher along all the process of coding and writing throughout this study.

Subsequently, for the *contexts*, the scope was focused on the purpose of this study, which is to understand the interaction among pertinent elements of critical thinking and mathematical thinking. Therefore, the researcher chose the perspectives of Facione for core skills of critical thinking and Schoenfeld for five aspects of cognition of mathematical thinking in determining the contexts, according to the related major consequences in the processes.

Next stage is to identify the *dimensions* to show property location on continuum. During the axial coding, ‘How’ question in the Conditional Relationship Guide identifies actions and interactions among the categories, the idea of dynamic process over time, and provides the depth that leads to the informants’ mode for understanding the consequences (Scott, 2004). Therefore, categories under the ‘how’ question of each category in the Conditional Relationship Guide, became dimensions for each particular process in the Reflective Coding Matrix. There was also possibility the same categories were identified as dimensions of different processes. Nevertheless, they were refined later after the Core Category was identified.

Another descriptor on the Reflective Coding Matrix to be taken into account is the *modes for understanding the consequences*. This descriptor is also known as process outcome. As mentioned above, categories identified as dimensions lead to the informant’s mode for understanding. Therefore, by having dimensions in place, helped the process of determining the modes for understanding the consequences. In this case, the modes were chosen among the major consequences.

Eventually, it is time to make an educated guess at what the Core Category might be. Initially, the researcher chose ‘decision to be made along the way’ as the potential Core Category due to the trend of processes. Then, returned to the data to find the information about decision to be made along the way from the informants in this study. How and why questions are raised and relation to the informants’ experiences is made for describing the chosen Core Category (Tuomela, 2005). In the explanation below, all codes are italicized.

Decision to be made along the way is one of the pertinent elements of mathematical thinking. It shows that the decision has to be made along the design process; at the preliminary stage, during designing and also during the construction. This concern behaviour is crucial in ensuring *compliance* to the requirements such as the needs of client and the concept of designing, and also in managing changes that are proposed along the design process. *Reviewing input data* especially during the preliminary stage, is an action of *concern behaviour* in *assessing the credibility of the data*, especially from the output of the data.

Therefore, having *tolerance to divergent views* is a way of adaption in facing the possible changes for decision making. By having this *open mindedness* disposition, easy for the engineers to *better understand others' opinions* and *working backward* to *revise* what have been done, and make some amendments if required, especially during the designing and construction stages. It helps in *forming conjectures* by considering others' views that lead to *drawing reasonable conclusion*.

Furthermore, to *defend conclusion or decision with good reasons* requires knowledge and experience. One way to do so is by using *analytical reasoning* in *selecting and pursuing the right approach*. *How efficient knowledge and experience is used* will *resolve alternative ways or solutions* to a decision to be made. Eventually, the decision has a tendency to be *dominating the orientation* on how the next steps will be done.

Paused at this stage, the researcher looked back at the Core Category that was initially presumed. In explaining about *decision to be made along the way*, all the processes in the Reflective Coding Matrix are engaged. From the processes discussed above, it shows that at all stages of designing, decision has to be made along the way, either due to expected or unexpected reasons. So, the researcher was contented that *decision to be made along the way* could be the Core Category.

Placing ‘decision to be made along the way’ in the Core Category block, enabling the researcher to fill in other blocks with categories that might work and support the Core Category and to make the whole fits the data. In doing so, the researcher was captured by the above statement saying the decision to be made has a tendency to be dominating the orientation of the next actions. Thus, the researcher let the Core Category to be refined as ‘decision to be made in dominating orientation’.

Then, returned to the earlier explanation about the decision to be made, the researcher found that most of the processes were supporting and leading to justifying decision in reasonable ways. Therefore, the Core Category is eventually refined as ‘***justifying decision reasonably in dominating orientation***’.

Properties are the last descriptor to be identified as they should be over-arching and more abstract than the categories themselves. Properties are reflecting characteristic of the Core Category. As dimensions show property location on continuum, and are determined at the earlier stage of developing the Reflective Coding Matrix, they are abstracted to a higher level in naming the properties.

The emergence of these key properties and modes of understanding the consequences is an indicator that the theoretical saturation is going to be reached (Scott, 2002). At this stage of analysis, once the Reflective Coding Matrix is fully developed, as shown in Table 5.17, the features of story line can be interpreted as a narrative story line incorporating a broad conceptualization of the meaning of all the informants. The refined Core Category depicts the process theory of justifying decision reasonably in dominating orientation.

The process theory developed in this study derived from field data collected through interviews with practicing civil engineers focusing on design process. An emerging grounded theory is not evaluated for its accuracy in describing or predicting a phenomenon of interest but its close adherence to the methodology in relevant to the informants studied (Glaser & Strauss, 1967). Therefore, a lot of emphasis was given in explaining the grounded theory process involving theoretical sampling and constant comparison in developing an emerging theory from data.

The fully developed Reflective Coding Matrix shows the refined Core Category, *justifying decision reasonably in dominating orientation*, with the six related processes: *complying requirements, forming conjectures, drawing reasonable conclusion, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach*. Figure 5.3 below illustrates six related processes identified for the refined Core Category which are extracted from the Reflective Coding Matrix.

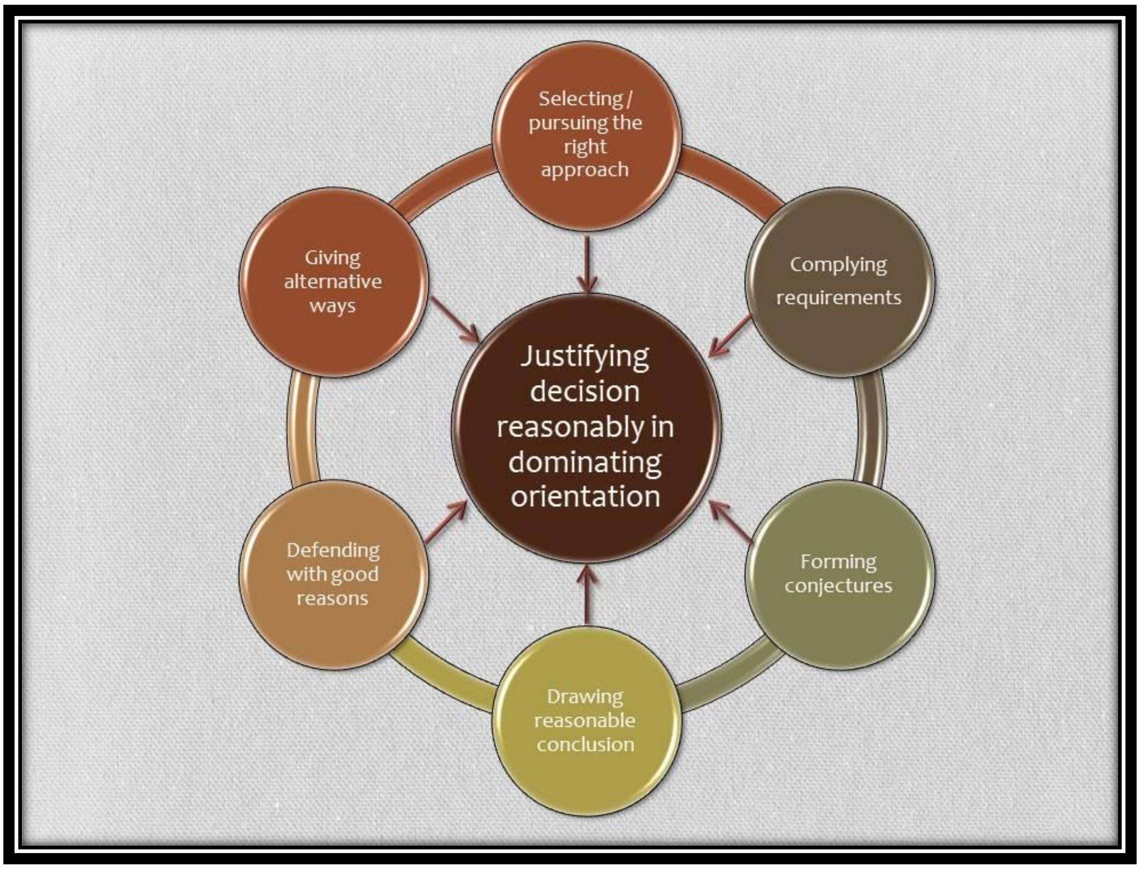
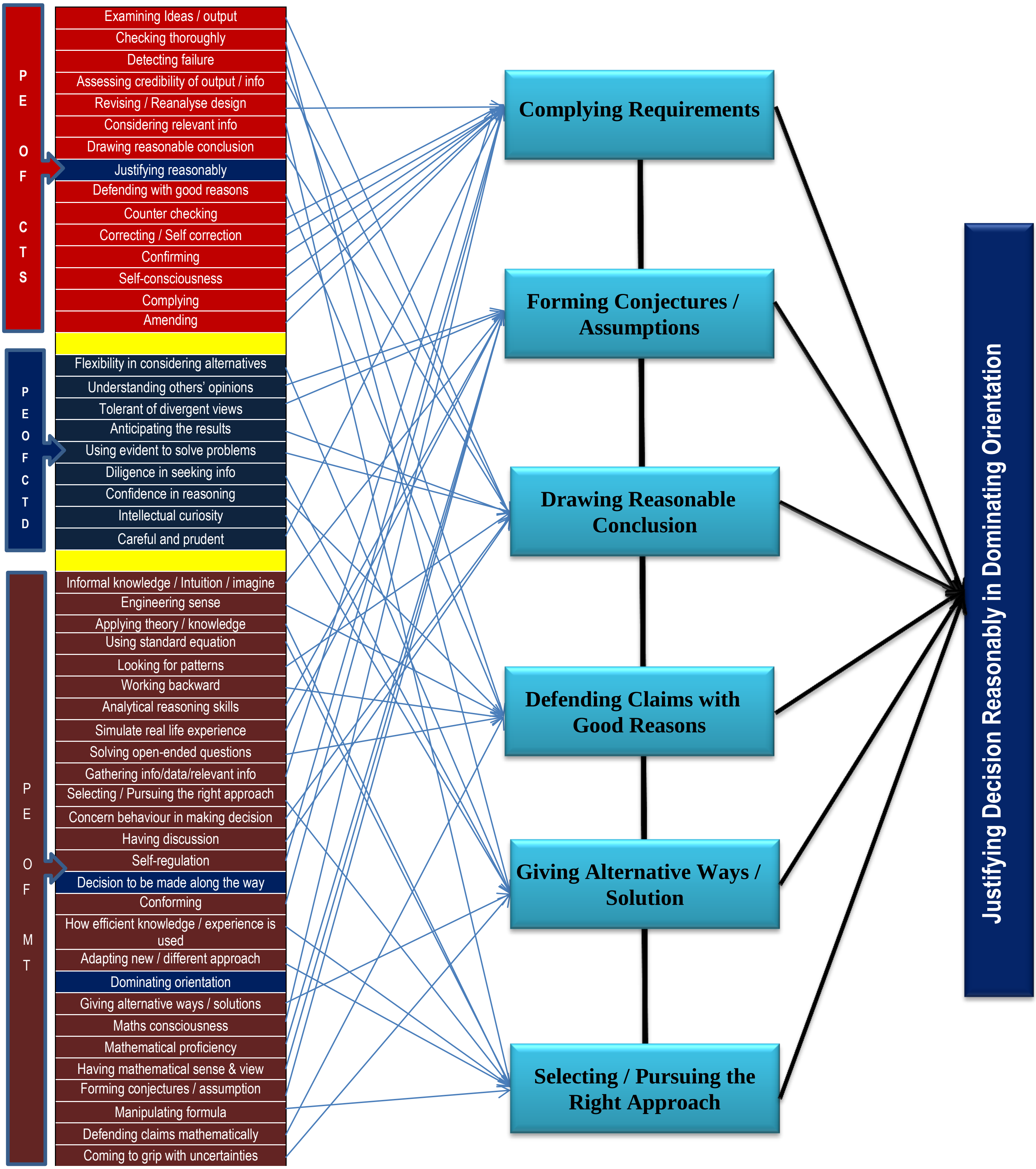


Figure 5.3: Six Related Processes for the Refined Core Category

Through the Conditional Relationship Guide and Reflective Coding Matrix, the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in developing the emerging theory are portrayed in the Figure 5.4.



PE – Pertinent Elements; CTS – Critical Thinking Core Skills; CTD – Critical Thinking Dispositions; MT – Mathematical Thinking

Figure 5.4: Interrelation and Interaction among Pertinent Elements of Critical Thinking and Mathematical Thinking

5.6 Development of Story Line

From the Reflective Coding Matrix, the explanation below explicitly describes the process theory, referring to the six essential processes: complying requirements, forming conjectures, drawing reasonable conclusion, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach. This explanation answers the third research question of this study regarding the interaction among pertinent elements of critical thinking and mathematical thinking. In the explanation, the researcher provides verbatim quotations from informants as support, and all quotations and codes are italicized.

5.6.1 Complying Requirements

Along the process, at all stages of designing, to be *complying* with the standard requirements is crucial and need to be taken into account. Ensuring all steps and measurements *conforming* to the specification like following the basic design process and adhering to code of practice is one's *self-consciousness* in putting in place his or her *self-regulation*.

We have its specifications in the BQ, as well as in the drawing. Meaning, it is within the specifications and does not deviate from what has been submitted. (E4)

Sometimes we mistakenly typed it and then passed to draftsman, I have read a saying "there is no such thing as simple mistake for civil engineer' and until now I do remember it, so, to the best possible, we have to minimize all the simple mistakes before producing the drawing. (E8)

Likewise, *confirming* a status prior making any decision is a part of *self-reflection* in addressing compliance. It needs to be done with *careful and prudent*.

There was a case, where, after the building was built, they found some cracks. We rechecking our design, running into software, and it was confirmed our mistake. We *had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks. (E7)*

Earlier, when the architects were still at their preliminary stage, we have already started our design, and in the end, they made changes, so, wastage in manpower, paperwork, therefore, now, we do not do it all out at the preliminary stage, once they have finished about 80% of the work, then only we step in. (E7)

In the same way, several aspects are in the main focus of compliance such as authorities' requirements, clients' needs and code of practice, especially the safety factors.

As long as we follow the specification, it means we are fulfilling their needs. If what we do is within specification, complete with its protection, we are freely to design without any problem. (E4)

Some of the clients, even though we have not got approval of the submission, they insist to proceed. We can only agree with them with condition that if later, there are any comments from authority, we have to follow and if they agree, then only we proceed. (E7)

Safety factor cannot be ignored, and the cost as well, so, by having an engineer can diversifies the design with minimal cost but safety is always prioritized. To me, this is the role of an engineer…….again, safety factor is our priority. (E7)

Equally important, to pursue the right approach in adhering the requirements involves some considerations like to do *self-correction*, having *mathematical consciousness* or *consciousness in assessing materials*.

After calculating the water demand, we do design, and after designing, if realized that we have over designed it, we can reduce the size from the result obtained using software. (E2)

Sometimes we do not aware about the new knowledge or materials at the factory or market, but the fact is they, and many other things out there, can help us and can be discussed. (E5)

In doing so, *gathering relevant information* is deemed necessary to have clear pictures and correct perspectives regarding the requirements. All the information is used for the purpose of *revising* and *amending* the design according to the specified requirements.

If we got comments from the authorities, such as, have to widen the drain or insufficient pond, then, we gather all the comments and forward to planner. (E8)

When we produce our output, it will be commented by several parties, then, we have to revise accordingly, and that's the second stage. (E5)

So, we will gather all the comments from each department and based on the comments, we will amend the layout. (E8)

Obviously, doing design tasks requires good time management. All comments, views and changes have to be handled in time. Therefore, the usage of design software is indispensable in keeping pace with the needs and urgency, either from the authorities or clients.

We must have design software, nowadays people do not design manually unless if want to be left behind. If clients ask us to do it today, they expect to get the result by tomorrow, so, for sure cannot finish if do it manually. (E1)

Undeniable, using software facilitates design works. Nevertheless, compliance to the requirement has never been neglected. Whatever the output produced by the software, it is always being monitored and *counter-checked*, especially for its compliance to the code of practice.

Software facilitates design. Nevertheless, we cannot neglect the code of practice. Even though we have software, we always have to do cross-checking, for example, we do a multi-storey building, we take certain area of the output, we check manually, whether correct or not the calculation done by the computer. We check its compliance to the code of practice, and once satisfied then only we proceed. (E7)

Software is used for doing calculation but for simple calculation we do it manually. We counter-check its output and make adjustment according to the specification. Thus, mathematical thinking is important in designing. (E2)

Hence, *complying the requirements,* as one of the processes in justifying a decision, is a fundamental process that not only to be considered at the beginning, but also during and after the design process. In other words, the process occurs along the way of designing, mainly when a decision is to be made, to be justified and to be dominating the orientation.

5.6.2 Forming Conjectures/Assumptions

Beginning at the preliminary stage of designing, the process of *forming conjectures / assumptions* has already been introduced for speculating what is going on and what will be happening. The assumptions are based on the preliminary information gathered during this initial designing stage.

Preliminary stage is for preliminary info, and from this stage we could make assumptions on what is going on. (E5)

Certainly, this process is not intuitive but an *adeptness* that needs to be gained and acquired. It is not only needed during the preliminary stage but at all stages of designing, especially when justifications are to be seeking out. *Adeptness* at *forming conjectures / assumptions* is one of the *mathematical proficiencies* applied in solving a problem. It is apparent that having *mathematical views and sense-making*, gives sound justification.

All stages involve mathematics, not so much at the input data, but, other than that, all involves mathematics. (E4)

Sometimes, when having high safety factor, columns and beams become bigger, in fact, if manually done, they can be smaller, can save cost, and clients also happy can save their money. (E7)

We follow a rule of thumb, if for column will be 6%, and if for IWK, usually will be based on unit, but, if we based on area, we already have our own table, so, we can estimate it. (E4)

In the same way, using *analytical reasoning skills* could support the process of *making conjectures* with more reasonable justification for a decision to be made.

Sometimes if we change the layout, infra will be affected, especially its flow path. For example, if having two pipe lines of water and sewer, plus with drainage, concerning about their flow paths, we have to find out, which one is lower than the other, and also the drainage… (E2)

For structure, we just enter into the software, but if it fails, we have to find out possible reason, maybe we have put too much loading, or have mistakenly doubled it, or maybe entered without loading, and one more thing, to look at its support direction, which all these could be factors of failure of a design for certain beams, slabs or columns. (E3)

More importantly, this analytical reasoning gives good prediction for *simulating real life experience* in *forming conjectures*.

…and for this, experience is helpful because we have to think of how will they execute it later, especially the contractor, if we do like this, how well can they do it? (E3)

It can be seen that the ability to *forming conjectures* is not solely depending on theoretical knowledge, it is mostly gained through experience and *informal knowledge* acquired with it as well.

Those skills come by experience, not stated in books….it is more to our experience, and experience teaches us a lot. (E1)

Thus, a lot of thinking is involved in forming conjectures mainly during the designing stage. This is not a random *imagination* but to facilitate designing, by imagining something that must be workable, adhering to the required specifications and able to be functioning.

We do thinking that needs an imagination, not like an artistic thinking that freely to think of anything, but we imagine something workable that considering all the required specification, we still have to imagine it so that it can be functioning. (E8)

Forming conjectures is a part of iterative design process that considering all possible views in making decision. For this, the engineers involved have always to be *tolerant of divergent views* and understanding others' opinions in order to make more comprehensive reasoning and justification for drawing a reasonable conclusion.

At the beginning stage, we have to confirm with client about the need statement, let say the owner wants to develop a bungalow, today he comes with this idea, so, we workout based on his idea, later, when we meet again, he has other different idea, so, this stage usually takes long time. (E7)

So far, I have never seen exactly the same approach been applied to different work, different clients have different ways and needs, so, we have to act accordingly, as long as it does not against our work ethic as an engineer.(E1)

5.6.3 Drawing Reasonable Conclusion

In designing a project, several decisions need to be made along the way of the process. Thus, having well attentive start as an initial scrutiny is deemed the first and foremost process in detecting, examining and having correct interpretation of a problem or situation. It's important *to comprehend* and *to clarify meaning* correctly when *examining ideas* or situations, to enable the engineers to really understand the problem.

When we want to design, we must aware of all the changes, and to understand the meaning of the changes. (E8)

At preliminary stage, after getting the architecture drawing, we have to study it and determine our layout structure. (E3)

In the same way, correctly *examining ideas* and *assessing credibility of statements* for making a decision and justification are important because it shows the degree of meticulousness and attentive effort to the decision process. This thoroughness is important in order to have a practically sound decision with *reasonable justification*.

Usually, from the architecture drawing, we could see where the beam, column and slab are placed, and if the columns having too big gap, we will ask permission from the architect to add some more columns, or otherwise the beam will be bigger. (E3)

Before producing the drawing, we will go through the output again, for both structure and infra, at least we go through again to check whether ok or not, then only we proceed. (E8)

For example, for installing a culvert at the place where the ground is not so strong, is it necessary to do piling for its foundation? After having discussion, we decided not to do it to let the culvert settle with minimum rate, because piling without doing *grounding treatment for the road will make the culvert bulging and this will cause problem to the road users.(E1)*

Subsequently, design process is done as team-working and no isolated silo mind-set. The engineers execute tasks based on specializations through frequent communications among team members along the process, and then, *having discussion* for coordination prior making any decision.

Definitely, we have a team in doing a project, consists of architects, engineers of civil, mechanical and electrical, quantity surveyor, and so on. We have to communicate very often, especially if there are any changes. (E7)

So, like having a team working, we work with consultants as a team, having another team working during design process, and after getting approval, we work as a team with contractors, so, we act like a middle-man, and we work close with contractor until the project finished. (E8)

…we have to know all, cannot miss any data, and must have sufficient data, and all this is done in a team, having discussion, again and again…. (E1)

In addition, to anticipate any reasonable conclusion or decision, *using evidence to solve problem* reflects better view of the real-world situation. It is due to every project is unique in terms of its needs, challenges and problems. Furthermore, ability to make inference or to anticipate any reasonable conclusion, using creativity besides technical thinking, as well as common sense is also crucial in designing.

We had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks. We panicked, at that time we had no professional engineer but only a supervisor, so, we sat down and discussed what had happened and how to rectify it. (E7)

Each project is unique, in the sense that each project has its own different problem and challenge. So, we need creative thinking, not only confine to technical…it needs common sense too. (E7)

Therefore, for design engineers, gaining experiences along the way of executing their engineering practices is priceless. It also includes having good rapport with other people in the field such as the authorities. This is to ensure smoothness of the work flow in the process of designing.

Having good rapport and experience is priceless, they can be adapted in other projects, but for layout, definitely different as it cannot be reused, except for schools that following JKR standards (E7)

Moreover, it is apparent that using software facilitates design works, and at the same time also accelerates design process to make it fast and reliable. Nevertheless, this comfort facility should not be a reason for being negligent to the miniscule detailing of the design, as it might affect the credibility of *drawing reasonable conclusions.*

It is undoubtedly that using software is very helpful…..but then again, when thing becomes easier, we always tend to be negligent, and our negligence makes us forget to see all the miniscule detailing, and this is really alarming and we need to focus on it. (E7)

5.6.4 Defending Claims with Good Reasons

Basically, to prioritize safety and minimize cost are the main factors being considered in designing a project, in fact, as the role and nature of practice of all design engineers. They should not compromise on safety to save cost. For having a strong fundamental to their decision, they must *defend their claims with good reasons*. All this comes with ethics and experience as experience matures the engineers with time. It helps them to *consider the relevant correct info* and to form sensible conjectures in designing a project.

Design is design, need is need, meaning, if client wants to save cost, we can consider the minimum design but still having buffer for safety factors. (E8)

…for gaining experience, it takes some time, it is there but we have to find the data, and the data must be correct, our assumption also must be correct, then only our design will be correct, and even later if it fails, it is not our faults but might be because of something else. (E1)

Another way in doing so is to *defend their claims mathematically* to let the decision sounds more practical and reasonable.

We cannot compromise on safety to save cost, we have our permissible limit, if the size of the beam really cannot be reduced, we have to defend it, and as an engineer, we indeed have to defend it. (E8)

As mentioned previously, software facilitates design works. Therefore, most of design tasks rely on the software. Having correct input data is important as it determines the product. Thus, *working backward* in *detecting failure* and in ensuring the correctness of input data is a very important process in designing. Again, experience adds some value in this case. When this part is verified, they can defend their claim with good reasons and justification.

Our input determines our product, if we find some peculiar things at our product, we have to re-check its basic input data in computer, and this part requires manual knowledge. (E1)

For senior engineers, those who ever did it manually, when it comes to software, they are more meticulous, they know where to check more detail, compared to those young engineers. (E7)

Subsequently, it is important to *defend claims with good reasons* during *solving open ended questions*. They have to make fast and accurate decisions in suggesting solutions to the problem. In this case, having strong *engineering sense* is indispensable and deemed necessary as design needs creativity.

When we investigated the soil, all was fine and we determined the place to do piling. But then, when they were doing the piling, the piling was broken, again and again, so, since we were facing the problem during that time, we had to make fast decision on what to do now, how to do….(E8)

If we are designing a building, where to put its beams and columns, where are the best position for them, and at the same time we want to minimize the columns because we want to minimize its foundation. So, all this comes from our sense, our creativity. (E8)

Therefore, adhering to the required specifications and complying with the design needs enable the engineers to defend claims with good reasons and justify decisions reasonably with confidence. This ethical professionalism also boosts confidence that their design is practical and workable.

We cannot neglect safety factors and related specifications in satisfying something, and at the same time, we must confident that the thing we are going to do is workable, and having confidence in our design. (E8)

5.6.5 Giving Alternative Ways/Solutions

As mentioned earlier, forming conjectures is one of the processes in justifying decision reasonably. This process inevitably affects the way they belief and see problems in designing. Additionally, when designing a project, their perception about the real situation usually steers their decisions.

Nevertheless, what they designed sometimes does not totally fit the real situation at site or maybe having difficulties to execute. As a result, *giving alternative ways or solutions* is a necessity in designing. They have to be *flexible in considering alternatives* as a *truth-seeking* practice, complementing their belief in designing a project.

Sometimes what we designed does not totally fit the real situation at site, or maybe difficult to execute, so, we have to think of other alternatives. (E3)

Usually we have to check it one by one, perhaps, some of the things we apply to the drawing is unnecessary, and maybe we can do it another way. (E3)

In view of that, *thoroughness in checking* on the design from scratch to the final output is going on from time to time, depending on level of confidence of the engineers and their *beliefs*. This is to ensure the concept of design is correct and fulfilling the needs of requirement.

Having the right concept from the beginning is important so that any perception made will be more reliable and practical. Therefore, they are able to think of how to solve problems in better way, to *grip with uncertainties*, as well as *giving alternative ways or solutions* to the problems.

Depends on their confidence, sometimes they come and seek for some advices, but I ask them to sit down together and check thoroughly the design concept as I am more satisfied to supervise from the beginning and not only at the end of the project.(E7)

…for SAJ, water supply and sewerage, it is challenging when having unexpected problem, such as blocking the existing pipe, so, we have to think of how to solve the problem, how to lay the pipe in order to have a good flow and we have to make suggestions. (E4)

Equally important, they have to know and understand clearly the client needs, as well as the requirements of authorities, in order to have the right concept of design from the beginning. Having *intellectual curiosity* helps the engineers to be *diligent in seeking relevant info* with much intense concentration and focus. It *affects* their perception and interpretation of the design concept to be more transparent. It enables them to propose more relevant alternative ways or solutions to problems in designing.

We have to know their needs, let say we build a road, how much depth is required, what is the purpose of building this road, or maybe we have to collect some data that is called traffic impact assessment to determine how many lanes are appropriate for the road. (E7)

Sometimes asking the local people, or the authorities about any new development there, if any, and the contractor also sometimes gives some info… (E2)

5.6.6 Selecting/Pursuing the Right Approach

Undoubtedly, theoretical knowledge and experience are equally important aspects in design that always interwoven and concurrently present. Those aspects are indispensable in dominating orientation for justifying a decision to be made.

When comes to the design concept, yes, we have to apply the theoretical knowledge like structure analysis and so on, but, when comes to real materialization on site, client's concern is only on cost saving, so, how confident are we, for example, if being asked, "This pillar is very big, can we reduce its size?" So, can we, off-hand, answer it, "Yes, it can be reduced", or we want to go back to the office to re-analyse it? Then, here is where the experience comes and dominating. (E7)

As each design project is unique in terms of its needs, problems and challenges, they have to *select and pursue the right approach* to ensure the design is fulfilling all the requirements and can be completed within the stipulated time.

If we want to get info in structure, we use the right formula and it is being well followed, but, how we approach our clients, it depends on individual skills to accelerate the process. (E7)

Obviously, the usage of software is dominating and indispensable in designing, to facilitates and accelerates the design process. Moreover, most of the calculations are done by software, but it never denies the importance and *the application of the theoretical knowledge* in designing.

Client wants all to be done fast. So, usually, we do a simple manual sketching, and then apply it to the software. We are not going to analysis it in detail one by one as the output of the software is quite reliable. Yes, the software indeed accelerates our design process. (E7)

Software is indeed a need; nevertheless, knowledge and theory we learnt during our study in university is also actually being applied, as it is being used in the software in the simplified form. So, the software just facilitates our job. (E8)

The theoretical knowledge, like *using standard equations*, may not be overtly applied but it is all embedded in the formula they use for doing calculation. However, when having a problem to trace or a need to review or amend the design, the theoretical knowledge is apparently used and directly applied. Also, some *manipulation* sometimes needs to be done on *the formula* to suits the requirement in getting the desired info.

Actually, indirectly, we use what we learnt, like calculus, and even though it is not directly applied, it is embedded in the formulae that we use for doing calculation. (E8)

Sometimes we cannot get the answer from the software, so, we have to manipulate an equation to get another calculation. (E3)

It can be seen that in designing, the process is not rigid but more flexible. The *ability to adapt experience or trying new or different approach* to meet the design requirement is deemed essential to the process. Even though each design project is unique, something invaluable from the experience is worth to be adapted to the next project. It includes techniques acquired in dealing with authority, like presenting theory and technical report, as well as building a relationship. Another thing is approaching techniques or having contact with expertise in the design field like expert in material defect. Equally important is having good rapport with others like authorities, team members, experts, and so on.

The longer he involves in a field, the more experience he gains, which can be adapted to the next projects. (E7)

Considering the above, it can be said that experience and knowledge add values to the engineers. Nature of work of engineering is to create and solve problems. Professional-wise, the engineers like to solve problems promptly and never left the problems with unattended. Therefore, they equip themselves with relevant knowledge and experience to sound more practical and reasonable in justifying a decision. Thus, it is *selecting and pursuing the right approach* leads the decision to be *dominating the orientation* with the *application and adaptation of the relevant knowledge and experience.*

In engineering, we create problem, and solve problems. We are the one who created the problem yet we solved it. Sometimes they do not know how to find the problem even the knowledge is there. For example, like designing a bridge, when we know the ground is not solid, so, what to do? We do SI test, from it, we know its foundation should be at this depth. So, we design it. Then, we found that the length is not sufficient, so, we extent some more, still not enough. Finally, the solution is, to add piling, then, have to calculate back. So, to get that experience needs someone to work longer…. (E1)

We do not come with unattended problem, we must act fast, meaning, we use our experience and knowledge to solve the problem (E 8)

5.7 Conditional Matrix

The details of the process theory explained in Section 5.6 are then visualized through a conditional matrix as shown in Figure 5.5. The conditional matrix is a coding device to help the researcher to keep in mind several key analytic points such as the processes and the consequences depicted in the Reflective Coding Matrix (Strauss & Corbin, 1998). The conditional matrix of this process theory is described as below:

a) At the center of the conditional matrix is the refined Core Category, *justifying decision reasonably in dominating orientation*, which is the central phenomenon of the study.

b) The inner rings of the conditional matrix represent the particular consequence of each process involved in justifying a decision, namely *tolerant of divergent views, concern behaviour, confidence in reasoning, flexibility in considering alternative* and *how efficient knowledge / experience is used* .

c) The outer ring of the conditional matrix represents the processes involved in justifying a decision, namely *forming conjectures, drawing reasonable conclusion, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach*.

d) The most outer ring of the conditional matrix placed the process, *complying requirements,* with its consequence, *careful and prudent*, represents as a fundamental to all other processes as explained in Section 5.6.1.

e) The thick green arrows that showing continuous direction at the most outer ring indicate the process is continuously taken into account at all stages of designing. The thin green arrows placed at the outer ring towards the center of the conditional matrix, segregating the five processes, are showing each process with its consequence involved in justifying decision reasonably.

This conditional matrix helps to further understanding of the interaction among the pertinent elements of critical thinking and mathematical thinking as explained in Section 5.6, which is embedded in the design process, as experienced by the practicing civil engineers.

Thus, the third research question of this study was answered by the explanation of story line of the process theory in Section 5.6 and the process theory was then visualized by the conditional matrix in Figure 5.5. Transforming the process theory into this integrative diagram is fulfilling the goal of this study.

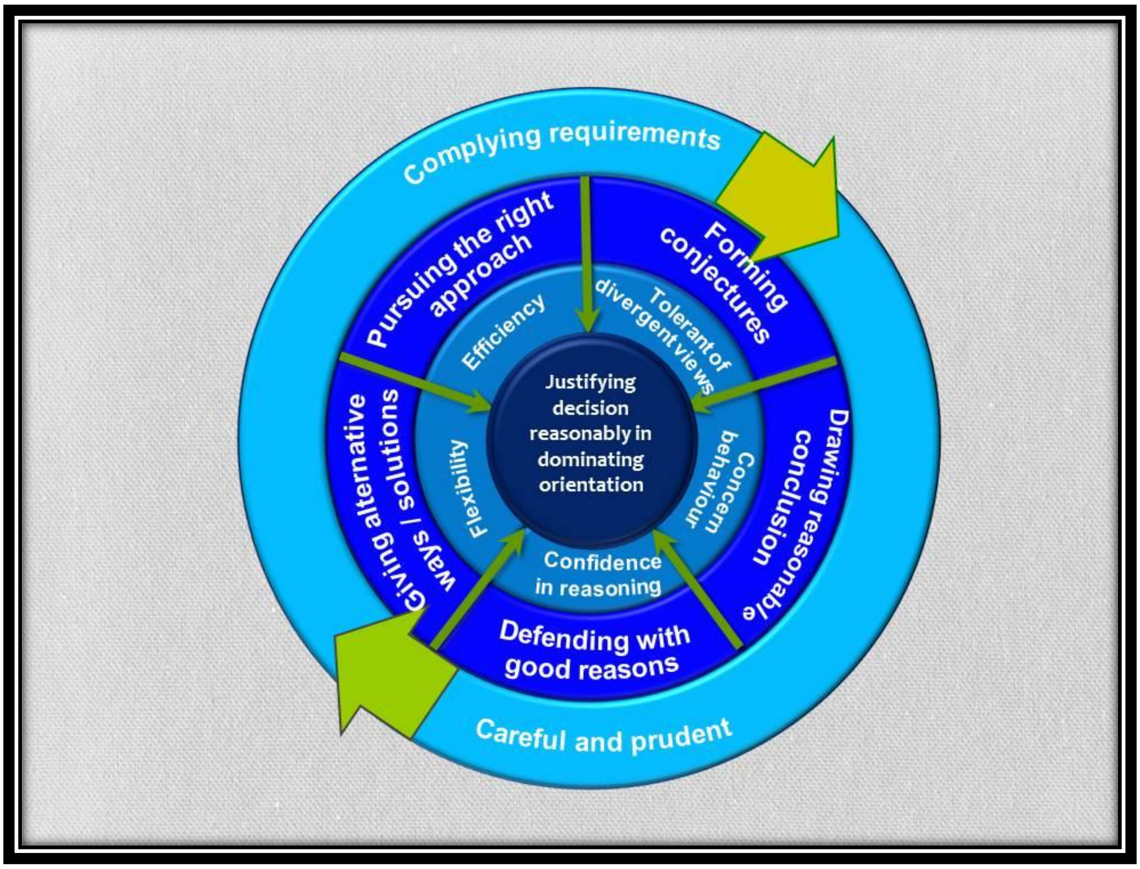


Figure 5.5: Conditional Matrix Representing Key Features of Process Theory

5.8 Summary

This chapter thoroughly explained about data analysis and the development of the story line. Data analysis process was visualized in the Figure 5.2 involving three basic analytic processes according to Strauss and Corbin, namely open coding, axial coding and selective coding.

a) Section 5.2 explained the execution of constant comparative method in achieving the theoretical saturation via theoretical sampling throughout the data analysis process.

b) Section 5.3 described in detail the open coding process, beginning with thoroughly reading through the interview transcripts until to the selection of the pertinent elements of critical thinking and mathematical thinking. Outcomes of this coding process served the answer for the first research question of this study.

c) Section 5.4 highlighted the utilization of the research tool named Conditional Relationship Guide, throughout the axial coding in interrelating the pertinent elements of critical thinking and mathematical thinking. The axial coding served the answer for the second research question of this study regarding the interrelation among the pertinent elements.

d) Section 5.5 discussed the process of developing the Core Category during selective coding through the research tool, Reflective Coding Matrix. The process theory was developed from the refined Core Category through the Reflective Coding Matrix which served a basis for answering the third research question of this study. The answer for the third research question was given in the forms of an explanation as presented in Section 5.6 and an integrative diagram as shown in Section 5.7.

e) Section 5.6 elaborated the process theory developed in the Section 5.5 through the development of the story line. This section explained in detail all the six essential processes related to the Core Category and its descriptors as depicted in the Reflective Coding Matrix in developing the substantive theory. Through the story line, this section provided an explanation regarding the interaction among the pertinent elements in answering the third research question of this study.

f) Section 5.7 presented the conditional matrix to visualize the process theory to further understanding of the interaction among the pertinent elements of critical thinking and mathematical thinking. The process theory was transformed into this integrative diagram to fulfill one of the goals of this study.

The next chapter discusses the interpretation and significance of the emerging theory in relation to the outcomes of data analysis described in this Chapter 5.

CHAPTER 6

DISCUSSION AND CONCLUSION

6.1 Introduction

This chapter consists of three parts which are respectively discussed in Section 6.2, Section 6.3 and Section 6.4. The first part discusses interpretations of the emerging theory from several aspects of study. It elaborates the emerging theory in relation to the research questions and the theoretical literature pertaining to critical thinking, mathematical thinking and engineering design process.

The second part discusses implications of the emerging theory for engineering education. This part illustrates the role of the emerging theory in mathematics and engineering instructions in relation to engineering criteria of Engineering Accreditation Council, Board of Engineers Malaysia (EAC-BEM). It explains how mathematics learning should be designed to enhance students' critical thinking and mathematical thinking and ability to solve engineering problems.

The third part, conclusions, explains limitations of the study and future research which discusses potential research themes and comments on methodology. To conclude this thesis, the closing section presents the summary of main contributions of this study.

Figure 6.1 shows the thematic structure for the organization of this chapter.

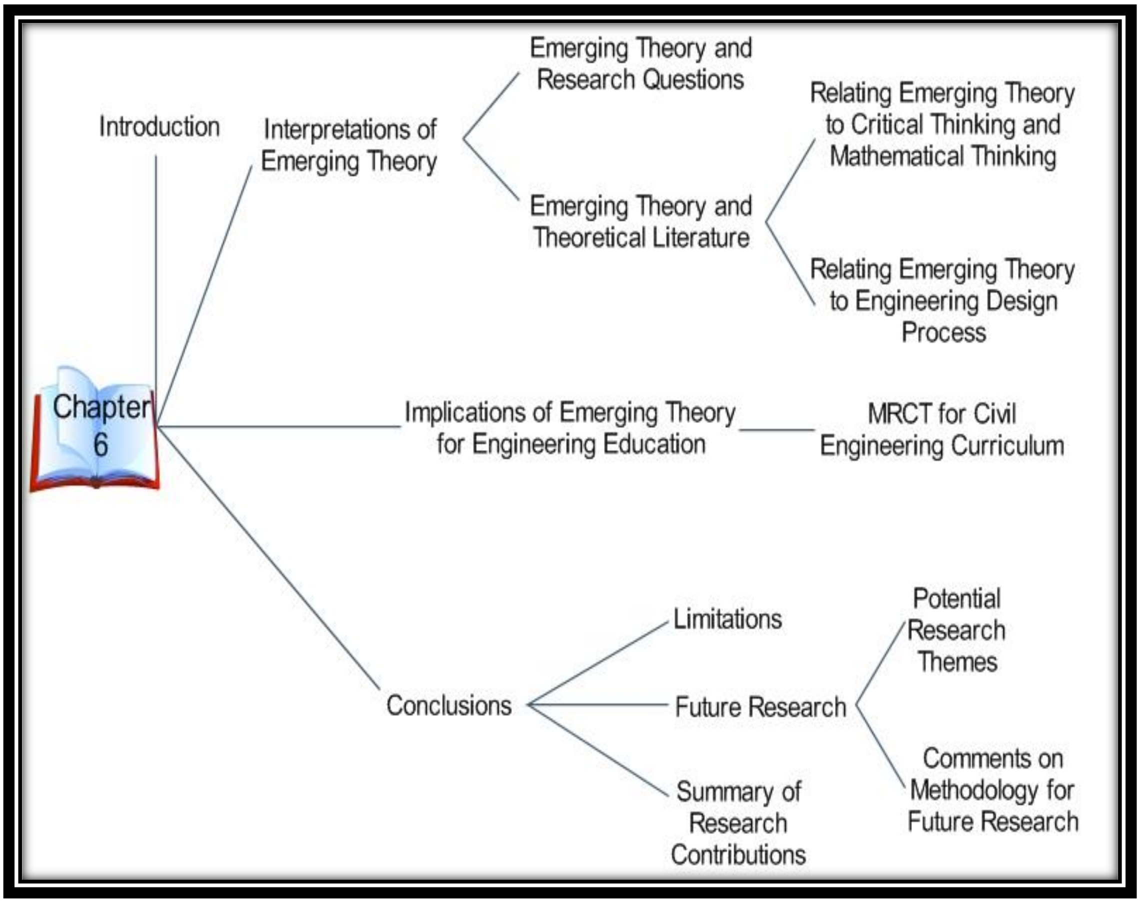


Figure 6.1: Thematic Structure of Chapter 6

6.2 Interpretation of the Emerging Theory

In this study, *making decision* was a prominent process occurred at all stages of designing, which being mentioned repeatedly by all the informants. It was identified as one of the twenty four major consequence categories. Through the iterative process of developing the Reflective Coding Matrix, it was refined and eventually fully described as *Justifying Decision Reasonably in Dominating Orientation* to be the emerging theory of this study. In brief, the theory reflects what a design engineer thinks when making decisions. Section 6.2.1 and Section 6.2.2 interpret in detail the emerging theory in relation to the research questions and theoretical literature.

6.2.1 Emerging Theory and Research Questions

The goal of this study was to develop a substantive theory pertaining to critical thinking and mathematical thinking used in real-world engineering practice. In view of that, it was important to have an insight into the interrelation and interaction among the pertinent elements of these two types of thinking. In this regard, this study centered to answer the research questions on what are the pertinent elements of critical thinking and mathematical thinking used in the civil engineering practice and how do the pertinent elements interrelate and interact during the execution of the practice. The research questions are interdependent. Figure 6.2 shows the interdependence of the research questions towards developing the substantive theory.

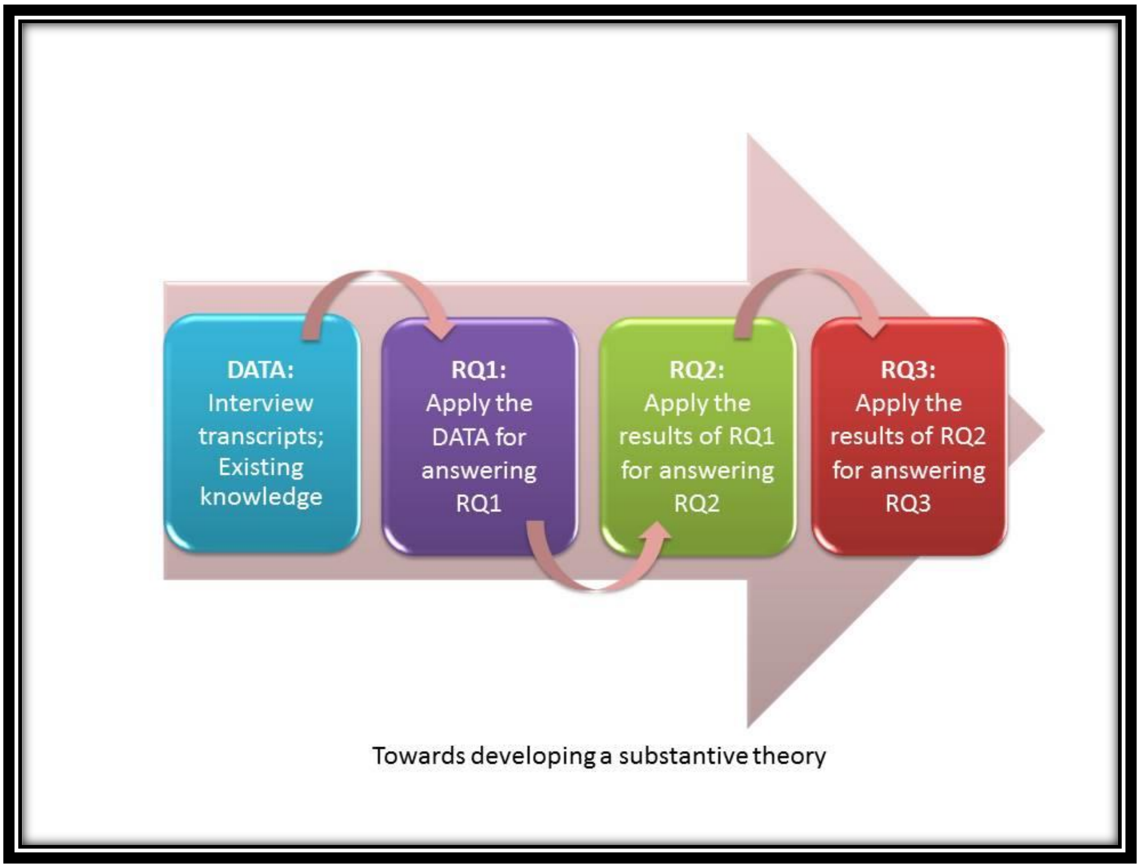


Figure 6.2: Interdependence of Research Questions

The interdependence of research questions is briefly discussed here. Since that the main concern of the first research question was to determine the pertinent elements of critical thinking and mathematical thinking, open coding process concentrated on identifying, selecting and categorizing the emerging codes regardless stages of design process. The pertinent elements identified from open coding process which also provided the answer for the first research question were the main data source for axial and selective coding process. These pertinent elements structured the foundation of the emerging theory which then supported the development of the emerging theory through axial and selective coding.

The interrelation among pertinent elements was then developed during axial coding, where the second research question was attended to. These interrelated pertinent elements were densely examined to identify the central phenomenon of the study or Core Category through selective coding. The interrelated pertinent elements ultimately integrated the emerging theory. The development of the emerging theory was comprehensively explained in selective coding, where the third research question was attended to. The interaction among the pertinent elements was explained in the story line of the emerging theory as can be found in Section 5.6. The theory was then visualized in the conditional matrix as depicted in Figure 5.5.

The first research question provides useful information to engineering education regarding the skills used in the real-world engineering practice. It helps engineering educators to identify and incorporate the pertinent skills from real engineering experience, as shown in Figure 5.4, into learning instructions. Thus, it helps the engineering educators to communicate the importance and relevance of the skills with professional practice to the students.

According to EAC-BEM (2012), the engineering curriculum should provide skills like analytical, critical and creative thinking to students. The students must also be equipped with the ability to apply engineering fundamentals and mathematical knowledge in analyzing and solving complex engineering problem. In view of that, the second and third research questions provide clear understanding to the engineering educators about the relevance of critical thinking and mathematical thinking to engineering courses. Further discussion about implication of the emerging theory for engineering education is given in detail in Section 6.3.

6.2.2 Emerging Theory and Theoretical Literature

This section closely discusses the relation between the emerging theory and theoretical literature pertaining to critical thinking, mathematical thinking and engineering design process. For that purpose, the emerging theory as explained in Section 5.6 and Figure 5.4 are thoroughly examined in relation to the theoretical literature for fit and relevance.

6.2.2.1 Relating Emerging Theory to Critical Thinking and Mathematical Thinking

Matlin (2009) defined cognition as mental activity that describes the acquisition, storage, transformation and use of knowledge that comprises a large scope of mental processes. Thus, the cognition operates every time receiving some information. Thinking, reasoning, decision making and problem solving are examples of cognitive process.

In this study, mathematical thinking was viewed from the lens of Schoenfeld (1985, 1992) for its five aspects of cognition, namely the knowledge base, problem solving strategies or heuristics, monitoring and control, beliefs and affects and practices. Therefore, the researcher looked into the mathematical thinking as having both cognition and cognitive process. Cognition comprises knowledge base, monitoring and control, and beliefs and affects. Problem solving strategies or heuristics and mathematical practices, which are about problem solving and decision making in selecting appropriate mathematical practices, are related to cognitive processes and affected by the cognition aspects. In other words, an engineer’s ability to use heuristics and mathematical practices were affected by the engineer’s knowledge base, capability to monitor and control and beliefs and affects.

Critical thinking as defined by Facione et al. (2000) and Facione (1990) is part of cognitive process according to Matlin (2009). Thus, problem solving and the use of mathematical practices during engineering design process were also affected by the engineer's critical thinking.

Based on the explanation mentioned above, together with the information extracted from Figure 5.4 regarding the interrelation and interaction among the pertinent elements, Figure 6.3 is generated. This figure visualizes the relation between mathematical thinking and critical thinking with respect to engineering design process. In particular, it shows the relation between critical thinking and mathematical thinking based on the emerging theory and a synthesis of literature.

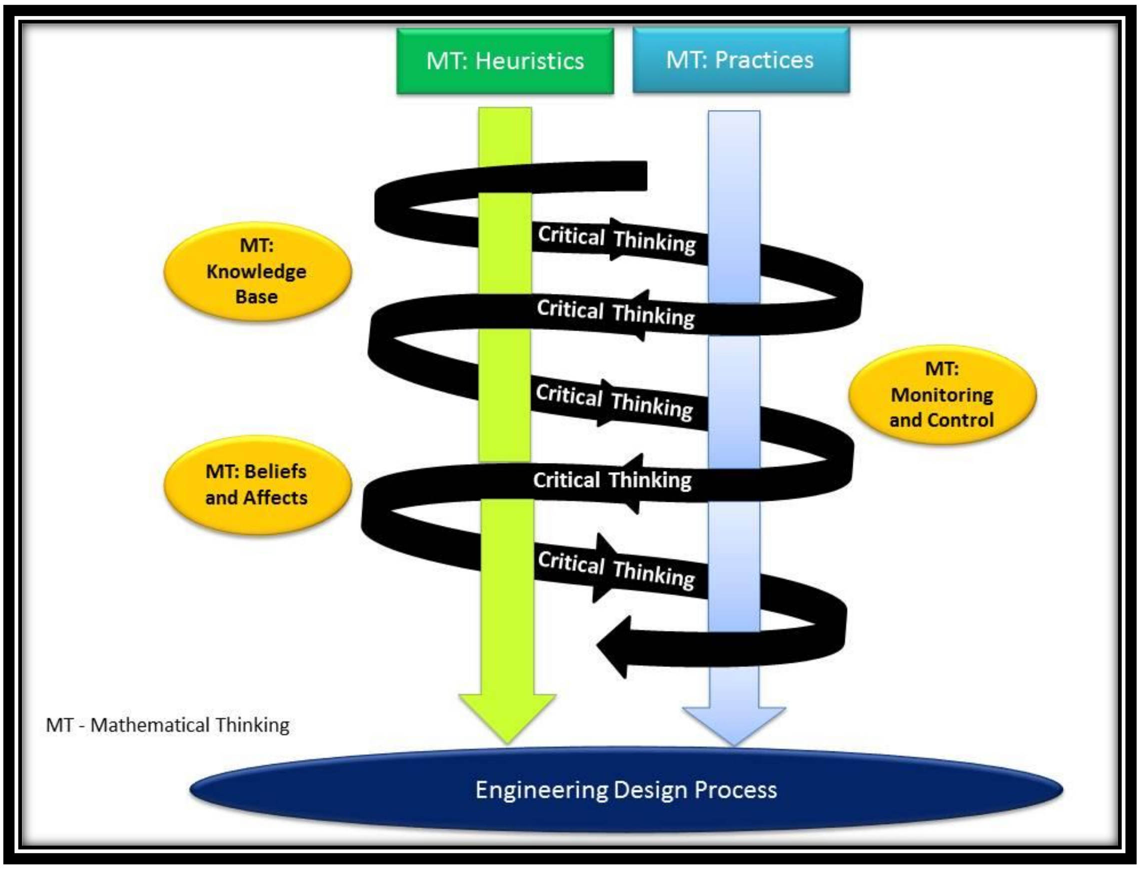


Figure 6.3: The Relation between Critical Thinking and Mathematical Thinking Based on the Emerging Theory and a Synthesis of Literature

A detailed discussion of the relation between the emerging theory and theoretical literature pertaining to critical thinking and mathematical thinking is as follows.

The Core Category or central phenomenon of this study was about a process of justifying decision reasonably. Returning to the review summary of definitions of critical thinking as tabulated in Table 2.1 and definitions of mathematical thinking in section 2.3.1, the relevance and closeness of the Core Category to the literature are examined in order to see the relation between the emerging theory and the theoretical literature.

As explained in section 5.5, the Core Category was refined to be *justifying decision reasonably in dominating orientation*, reflecting processes involved in making decision in engineering design process. The main focus was on making and justifying decision reasonably. Six essential processes involved as action and interaction in justifying decision were *complying requirements, forming conjectures / assumptions, drawing reasonable conclusion, defending claims with good reasons, giving alternative ways / solutions and selecting / pursuing the right approach*. The characteristics of justifying decision reasonably in reference to the action and interaction processes were identified as having self-consciousness, adeptness, anticipation, justification, perception and adaptation.

Referring to Table 2.1, the definitions of critical thinking mentioned about thinking that has a purpose, reasonable and self-directed that facilitates good judgment. *Complying requirements*, involving *self-consciousness* in the context of *self-reflection*, was resulting in a *careful and prudent* attitude in making a decision. Lipman (1988) defined critical thinking as a self-correcting and responsible thinking that facilitates good judgment. It shows that in the process of *complying requirements* involved critical thinking as defined by Lipman. Paul and Elder (2008) were in accord with Lipman about self-corrective thinking, besides asserting critical thinking as the art of analyzing and evaluating thinking with a view to improve it.

The process of *complying requirements* covered several aspects of critical thinking and mathematical thinking as dimensions to the *self-consciousness*. As depicted in the Reflective Coding Matrix, in reference to Facione (1990, 2013) and Table 5.12, *confirming, self-correction, counter checking, revising and amending* were categorized as pertinent elements of critical thinking. In the same way, *conforming, gathering relevant info, self-regulation and mathematical consciousness* were identified as pertinent elements of mathematical thinking according to Schoenfeld (1992) and Table 5.14.

As discussed in section 5.6.1, *complying requirements* was the fundamental process which to be considered along the way of designing, mainly when a decision was to be made, justified and dominating orientation. Since the *complying requirements* inclined more to critical thinking, it could be presumed that having critical thinking is the fundamental in justifying decision reasonably throughout the design process.

Forming conjectures/assumptions in the process of making decision required *adeptness* in *making analytical reasoning, simulating real-life experience, using informal knowledge/intuition, understanding others' opinions* and *having mathematical views and sense making*. The way experts engage with mathematical practices was considerably different with school mathematics (Schoenfeld, 1992). Proficiency in using and engaging in mathematics affects problem solving orientation in terms of using mathematical practices and mathematical thinking.

Schoenfeld (1992) also noted that beliefs and affects toward mathematics impact the appropriateness of using mathematics and engaging in mathematical thinking. In design process, the *proficiency* was built from engagement in mathematical practices and performances with experience and knowledge that increase confidence to be *tolerant to divergent views*. Bailin et al. (1999), Ennis (1987), Facione et al. (2000) and Facione (1990) regarded the behavior of considering others' point of view as one of the critical thinking dispositions.

Likewise, mathematical practices engaged by an engineer were influenced by the engineer's critical thinking, as revealed in axial coding that the pertinent elements of critical thinking and mathematical thinking were interrelated among each other during the engineering design process. Findings from the previous study showed an image of congruence between critical thinking and mathematical thinking in the process of solving civil engineering problems (Radzi et al., 2012).

Subsequently, the process above leads to *drawing reasonable conclusion* by taking into account *inferences* made for the *anticipated decision*. Consequently, it caused an engineer to be having a *concern behavior* in *comprehending and clarifying meaning, examining ideas and assessing credibility of statements*. The *concern behavior* requested the engineer to have analyticity in *using evidence to resolve problems* as defined by Facione (2013) for the disposition of critical thinking.

Engineers looked for patterns of previous experience before making inferences in drawing any conclusion and the conclusions were made based on discussion among the engineers and team members. Referring to Table 5.14, *looking for patterns* and *having discussion* are pertinent elements of mathematical thinking related to problem solving strategies or heuristics and monitoring and control, respectively. Schoenfeld (1992) identified that problem solving performance was enhanced when engaging in self-monitoring and controlling activities. This relation of heuristics and monitoring and control has been mentioned in section 2.3.3 which highlighted the importance of having discussion during the process of problem solving (Schoenfeld, 1992).

Another process in justifying decision reasonably was *defending claims with good reasons.* Being justice is a criterion in making reasonable judgment as developed through the reflective coding matrix that *justification* was a characteristic of the emerging process theory. Paul (1990) stated that having an intellectual sense of justice, which is one of the seven interdependent traits of mind, makes a person to be a strong-sense critical thinker. Bailin et al. (1999) defined critical thinking as thinking that aimed at making judgment and must be directed towards some purpose such as answering a question, making a decision, solving a problem, resolving an issues and devising a plan.

In the same view, the design engineers set an iteration plan in making and justifying decision in the engineering design process. The engineers carried out the plan such as having intellectual sense of justice in *considering relevant info, working backward*, and using *engineering sense in defending claims mathematically* and *solving open ended questions* for the purpose of *defending claims with good reasons*. The strategies involved mathematical heuristics, practices and knowledge base respectively for the solving open ended questions and working backward, defending claims mathematically and using engineering sense, according to the aspects of cognition of mathematical thinking (Schoenfeld, 1992).

Facione et al. (2000) and Facione (1990) were in accord with Bailin et al. (1999) in defining critical thinking as thinking that serves a purpose for leading a person to form a judgment. Facione also asserted that the person must have a critical spirit that inclines to critical thinking. Complementary to this, the engineers showed *confidence in reasoning* with the support of the iterative plan in making and justifying decision while giving *explanation* for the purpose of *defending claims with good reasons*. In other words, the engineers defended claims with good reasons by having confidence and intellectual sense of justice in explaining and executing the plan during the engineering design process.

As mentioned above, Schoenfeld (1992) noted that beliefs and affects toward mathematics impact the appropriateness of using mathematics and engaging in mathematical thinking. Again, this phenomenon could be seen in *giving alternative ways or solutions* in making and justifying decision reasonably. In a wider scope of application, an engineer's *belief and affect* toward problem solving in engineering design influenced the engineer's *perception* in *giving alternative ways or solutions* in solving a problem. According to Paul and Elder (2008), critical thinking is the art of analyzing and evaluating thinking with a view to improving it. Accordingly, the perception determined the engineer's *flexibility in considering alternatives* to be more *coming to grips with uncertainty, diligence in seeking info, checking info thoroughly* and having *intellectual curiosity*.

The characteristic of the engineer for being *diligent in seeking info* was considered as having one of the critical thinking dispositions from the lens of Facione et al. (2000) and Facione (1990) and Ennis (1987). In the same view, Bailin et al. (1999) together with Facione et al. (2000) and Facione (1990) and Ennis (1987) regarded having an inquiring attitude as the *intellectual curiosity* in order to be well informed was a critical spirit that inclined the engineer's thinking to think critically.

Facione et al. (2000) and Facione (1990) and Bailin et al. (1999) shared the same view that critical thinking is thinking that must be directed to some end or purpose. Ultimately, the engineers had to make a *selection for and pursue the right approach* after taking into account relevant aspects from other processes in the emerging theory in making and justifying decision reasonably. The process required an *adaptation* in *applying theory or knowledge, experience, new or different approach*, and in *using standard formula or equations* in engineering design process.

Schoenfeld (1992) viewed these adaptation strategies as *monitoring and control* and knowledge base for the aspects of cognition of mathematical thinking. These two aspects of cognition influenced the engineer in *manipulating formula or equations*, as explained and visualized in Figure 6.3 above. The process of *selecting and pursuing the right approach* determined *how efficient knowledge and experience was used* throughout the engineering design process in justifying decision reasonably in dominating orientation.

Looking again at the detailed discussion above in relating the emerging theory to critical thinking and mathematical thinking, and after considering these essential elements, the researcher intends to name the process theory as Math-Related Critical Thinking (MRCT). The name is chosen in view that the pertinent elements of critical thinking involved were inclined to and interrelated with mathematical thinking in justifying decision reasonably in dominating orientation.

Thus, MRCT is a substantive theory which explains the interrelation and interaction between critical thinking and mathematical thinking. In particular, this emerging theory is a process theory explaining the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice. It provides useful empirical information to engineering education about the relation between critical thinking and mathematical thinking in the real-world engineering practice, which is currently still lacking in the available literature.

The useful empirical information relating critical thinking and mathematical thinking in solving complex engineering problem with respect to engineering design process is explained in detail in the following section.

6.2.2.2 Relating Emerging Theory to Engineering Design Process

The emerging theory explained about six action and interaction processes involved in justifying decision reasonably in dominating orientation. It was about making and justifying decision reasonably in engineering design process. Khandani (2005) explained about the Engineering Design Process (EDP) that consists of five processes, namely, defining the problem, gathering information, generating multiple solutions, analyzing and selecting a solution, and testing and implementing solution.

As EDP is used in a problem-solving works for design problems, decision making is important in managing the design process (Ullman, 2001). In Beyer (1984), six steps of decision making were mentioned: stating the desired goal or condition; stating the obstacles in realizing the goal or condition; identifying the alternatives available for over-coming each obstacles; examining the alternatives in terms of the resources needed to carry them out, the costs involved, and the constraints inherent in their use; ranking the alternatives in terms of their probable consequences; and choosing the best alternative.

Table 6.1 shows the comparison between the EDP, emerging theory, and decision making. EDP is used for solving design problems which involve the process of making and justifying decision. The process may require backtracking and iteration as the solution is subjected to unforeseen complications and changes as it develops (Khandani, 2005).

Table 6.1: EDP, Decision Making and Emerging Theory

Engineering Design Process (EDP) (Khandani, 2005)	**Decision Making (Beyer, 1984)**	**Justifying Decision Reasonably in Dominating Orientation**
Defining the problem	Stating the desired goal or condition	Complying requirements
Gathering information	Stating the obstacles in realizing the goal or condition	Forming conjectures / assumptions
Generating multiple solutions	Identifying the alternatives available for over-coming each obstacles	Drawing reasonable conclusion
Analyzing and selecting a solution	Examining the alternatives in terms of the resources needed to carry them out, the costs involved, and the constraints inherent in their use	Defending claims with good reasons
Testing and implementing solution	Ranking the alternatives in terms of their probable consequences	Giving alternative ways / solutions
	Choosing the best alternative	Selecting / pursuing the right approach

Since the emerging theory focuses on making and justifying decision in engineering design process, further explanation relates the emerging theory with engineering design process (Khandani, 2005), decision making (Beyer, 1984) and associates elements (Appendix C) that emerged during open coding. The five-step model of EDP by Khandani (2005) and six steps of decision making mentioned in Beyer (1984) are chosen for its moderation and suitability that relevant and fit to be discussed with the six processes of the emerging theory. While the associate elements listed in Appendix C helps the researcher to understand more about the design process. The explanation is based on the virtual sequential process order starting from EDP, decision making and emerging theory for the purpose of discussion in this section.

The first step in the design process was *defining the problem*. The definition contains a listing of information about the product or client requirements (Khandani, 2005). Relatively, in decision making for solving problems, the engineers *stated the* *desired goal or condition* (Beyer, 1984) that fulfilling the design requirements. Creating a clear list of the requirements in defining and solving the design problem was crucial as it may evolve throughout the design process. Therefore, for justifying the decision reasonably, *complying* to design standard and *requirements* is a necessity along the process of designing. *Adherence to the design standard and practice* such as *following design process, codes of practice and the requirements of authority and client* were matters to be taken into account during the design process.

Moreover, ability to justify a solution to an engineering problem based on professional and ethical standards is one of the twenty-four outcomes that need to be fulfilled by an engineer before entering into the practice of civil engineering at the professional level (BOK2 ASCE, 2008).

The next step was *gathering pertinent information* (Khandani, 2005) regarding the design requirements from the lens of relevant *authority, client* and other related personnel in executing the design process. To have a good *communication skill* was seen as an advantage and important criterion in design especially when dealing with *team members* and other parties in gathering the required information and building *good rapport*. It is an attribute of an engineer to be able to communicate effectively on complex engineering activities with the engineering community and with society at large (ABET, 2014; EAC-BEM, 2012).

In addition, an engineer has to function effectively as an individual, and as a member or leader in diverse teams and in multi-disciplinary settings (ABET, 2014; EAC-BEM, 2012). *Having good rapport* and *relationship* with those related personnel together with *experience in dealing with authority* for *presenting theory and technical report* smoothened the process of obtaining the relevant information. The information helped the engineers to *identify and foresee obstacles in realizing and meeting the design requirements* (Beyer, 1984) during the decision making in solving the design problem. This information was manipulated by the engineers using their *engineering sense* and *imagination* for *forming conjectures or assumptions* in justifying the decision.

Once the details of the design were clearly identified, the *design team* worked with *creativity* on *specialization and coordination* basis to *generate multiple solutions or alternatives* in order to achieve the goal and requirements of the design (Khandani, 2005). In making decision, the engineers *identified those alternatives available for over-coming each obstacle* (Beyer, 1984) based on information gather through the *engineering sense, knowledge and experience*. Ability to observe and *see from different angles of view* together with *personal attributes in design* such as *having interest, patience, persistence, initiative and confidence* helped the engineers to *apply and transfer knowledge and experience* in drawing reasonable conclusion. From that, the *process of analyzing and selecting* the most promising alternatives was executed by *examining the alternatives in terms of the resources needed, cost involved and possible constraint available* (Beyer, 1984; Khandani, 2005).

The task of the engineers was to *prioritize safety and minimize cost*, which were seen as the most important criteria to be considered during design process. In the context of minimizing cost in designing, the usage of software that facilitates and accelerates design process was indispensable especially in dealing with time constraints and meeting deadlines. Thus, it is important for the engineers to understand mathematics and scientific fundamental behind the software tools and techniques they are using (King, 2008).

The engineers have to possess the ability to use the techniques, skills, and modern engineering and information technology tools necessary for engineering practice (ABET, 2014; EAC-BEM, 2012). By analyzing the alternatives from all angles of view and in the meantime, ensuring these important criteria were adhered to, enabled the engineers to *defend claims with confidence and good reason*. The engineers were then *ranking the alternatives in terms of probable consequences* (Beyer, 1984) in *giving alternative ways or solutions*. Detailed design and analysis process enabled the engineers to *choose the best alternative* and *the right approach* to be implemented (Beyer, 1984; Khandani, 2005). The selection that best fits the design requirements dominating the orientation of justifying decision reasonably in solving problem and decision making during engineering design process.

As mentioned earlier, the EDP, decision making and justifying decision reasonably are continuous iterative process that may require the engineers at any point of the process to go back to the previous step. In the nutshell, these three main processes were interconnected and interrelated along the way of engineering design process as represented in the following Figure 6.4.

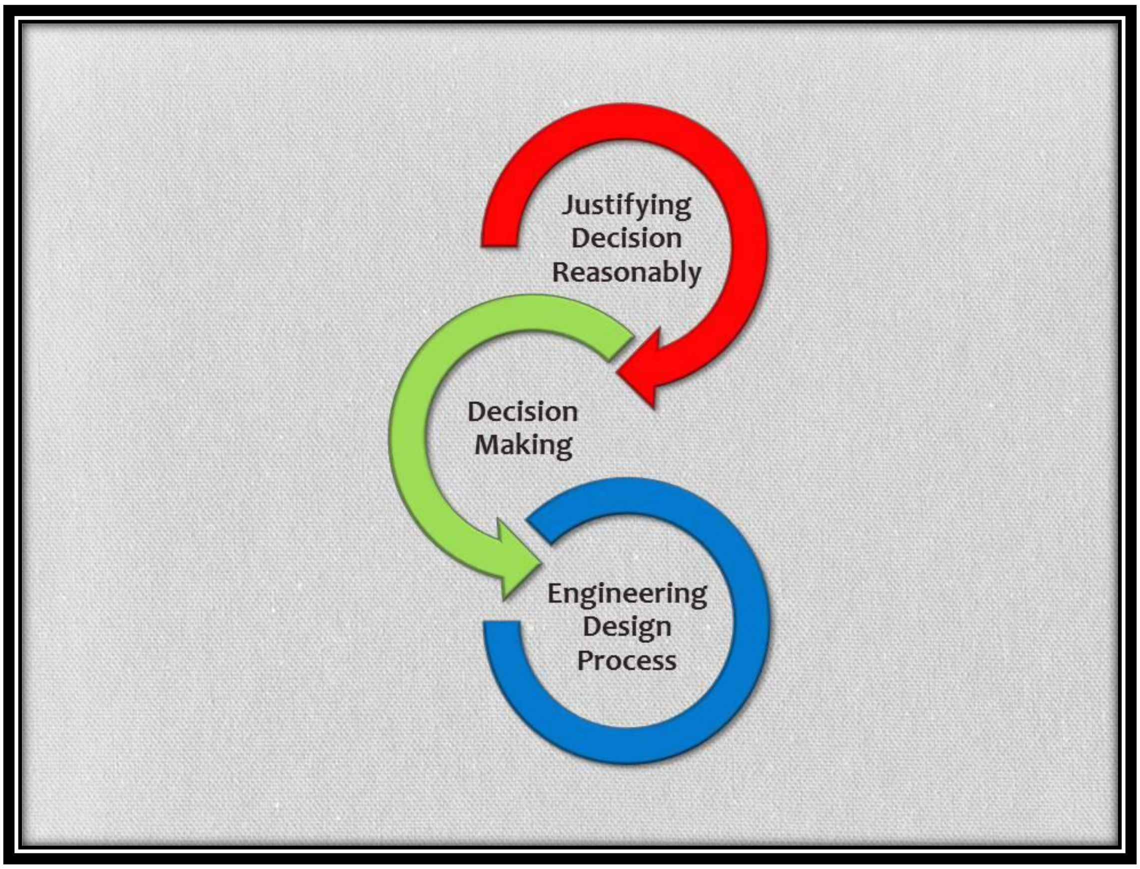


Figure 6.4: The Interrelation between EDP, Decision Making and Emerging Theory

An explicit description of the process theory emerged from this study regarding the processes involved in making decision is not only useful for engineering education but also needed for engineering practice, which is currently still lacking in relation to the engineering design (Hatamura, 2006).

6.3 Implications of Emerging Theory for Engineering Education

Promoting critical thinking and problem solving in mathematics education is crucial in the development of mathematical thinking of successful engineering students. Critical thinking and problem solving go hand in hand. In order to learn mathematics through problem solving, the students must also learn how to think critically (Marcut, 2005). Section 2.2.6 has discussed several points about the needs to teach critical thinking to engineering students. Additionally, findings from the previous study have shown an image of congruence between critical thinking and mathematical thinking in the process of solving civil engineering problems (Radzi et al., 2012).

Furthermore, the engagement between critical thinking and mathematical thinking in civil engineering practice seems a workable pair complementing each other. A very well-known meta-framework for instructional design is presented in the How People Learn (HPL) model, described by Bransford, Brown, and Cocking (1999) has identified the four areas that instruction should include to maximize learning. According to this paradigm, instruction should be student-centered (driven by the knowledge, skills, attitudes and needs of the learner); knowledge-centered (focused on helping learners develop a deep understanding of the content and processes of the discipline); assessment-centered (keyed to both formative and summative evaluation with frequent and informative feedback and revision); and community-centered (based in a community of learners within the learning situation and connected to the community at large) (Svinicki, 2010). This study seems to provide some useful empirical information that can be incorporated into engineering education mainly in the area of student-centered and knowledge-centered learning.

Student-centered is driven by the knowledge, skills, attitudes and needs of the learner. It consists of two major divisions of learning theories: Cognitive theory and Social Cognitive Theory (Svinicki, 2010). Cognitive theory is meant for learning facts and principles, like mathematics. Whereas social cognitive theory is meant for learning skills and procedures, including intellectual skills like critical thinking. It seems like the engagement between critical thinking and mathematical thinking in civil engineering practice is a workable pair complementing each other, in relation to the theories of student-centered learning.

As mentioned in the section 2.6, a number of studies have been conducted on critical thinking (see, for example, (Aizikovitsh & Amit, 2009, 2011; Douglas, 2006, 2012a; Jacquez et al., 2007; Luan & Jiang, 2014; Marcut, 2005; Norris, 2013) and mathematical thinking (see, for example, (Burton, 1984; Cardella & Atman, 2007; Cardella, 2006; Kashefi et al., 2012a, 2012b; Rahman et al., 2013; Yusof & Rahman, 2004), in relation to mathematics and engineering. Unfortunately, there is no study on both critical thinking and mathematical thinking, mainly on the use of both thinking in real-world engineering practice. Therefore, in this study, having insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking is to empirically correlate part of cognitive theory and social cognitive theory, represented by mathematical thinking and critical thinking respectively.

Similarly, the knowledge-centered learning focuses on helping educators develop a profound understanding of the content and processes of the discipline. A research conducted by Idrus et al. (2010) has proven that critical thinking and problem solving skills have been placed as the most important soft skills to be taught to engineering students. However, the finding from the research has also revealed that the implementation of critical thinking was not clearly captured by the students in the teaching and its relevance to their profession was also not clearly addressed. It was because the lecturers might not have explained explicitly the learning contents and outcomes and the importance of the engineering real-practice skills to be developed by the students in the lesson. In this regard, it is important to ensure the students understand the relevance of the skills to be developed to their professional success (Woods et al., 2000).

In social learning theory, Bandura stated that the theory deals with aspects of learning and motivation and regarded social interaction as a medium in the process of learning and development (Bandura, 1977; Svinicki, 2010). The theory said that learning was greatly influenced by the vicarious learning capacity that represents one part of the motivational aspect of social cognitive theory. In the same view, engineering educators are role models that give impact to students in terms of their attitudes, emotions, beliefs and affects about the learning contents. As such, the emerging theory of this study might help engineering educators to have better insight into MRCT in the real-world engineering practice to better prepare the engineering students to be equipped with the pertinent professional-related skills. Furthermore, Felder (2012) in a tale of two paradigms in engineering education mentioned that the integrated engineering curricula for engineering education should be infused with real-world engineering problems and balanced with contents and skills such as analytical and critical thinking, problem solving, teamwork and communication.

This study provides evidence to engineering education about the usage of both critical thinking and mathematical thinking in real-world civil engineering practice. This information helps engineering community towards better balance engineering curriculum with the skills required and applied in real engineering practice. Several aspects regarding the real-world engineering practice and engineering education need to be pondered along the way towards preparing the better and balance engineering curriculum, are discussed as follows.

Teamwork - In engineering practice, the engineers usually work as a team to solve engineering problems while in engineering education, problem solving is mostly an individual effort. The engineers work according to the particular areas of specialization and then put the effort together in symbiotic cooperation for coordination. In doing this, communication skill is important to initiate good relationship between team members and building good rapport with other individuals or parties involved. Besides communication skill, it is adhering to engineering standards and having self-discipline to ensure smoothness and success of a project that counted. These attributes could be instilled in engineering students through team-working activities in engineering education.

Knowledge transfer **-** In engineering practice, knowledge and experience are intensely used to estimate and give alternative ways or solutions to real problems before selecting or pursuing the right approach. While in engineering education, knowledge is domain-related and mostly used to derive a specific and exact solution to theoretical problems. In most cases in engineering practice, knowledge is implicit and embedded in the engineering process because real engineering problems are often ill-structured and having lack data compared to problems encountered in engineering education that usually well-structured.

Computer proficiency – In modern engineering practice nowadays, computer application is indispensable in facilitating engineering tasks and accelerating works in meeting deadlines. Engineers do have difficulty interpreting and analyzing computer output and sometimes may generate errors due to lack of understanding in reading the computer solutions. Mathematical formula and calculation are intensely used yet embedded in the engineering software. Understanding this implicit knowledge may help the engineers to do problem solving using computer analysis. While in engineering education, engineering students' reliance on computer application is outstanding. However, the students should be trained to do data analysis using computer and engineering software applications, which is somewhat being neglected in engineering education. Adjustment and adaptation to the usage of computer and software familiarization in engineering education is deemed necessary to be at par with that in real engineering practice.

Thus, this research was aimed to contribute to a body of knowledge useful empirical information that might help faculty and curriculum stakeholders to better prepare engineering students to use MRCT to make meaningful contribution to real-world engineering practice. It helps the engineering educators and students to have clear understanding about the relevance of the skills with engineering courses. Figure 6.5 below shows the emerging theory in relation to engineering education.

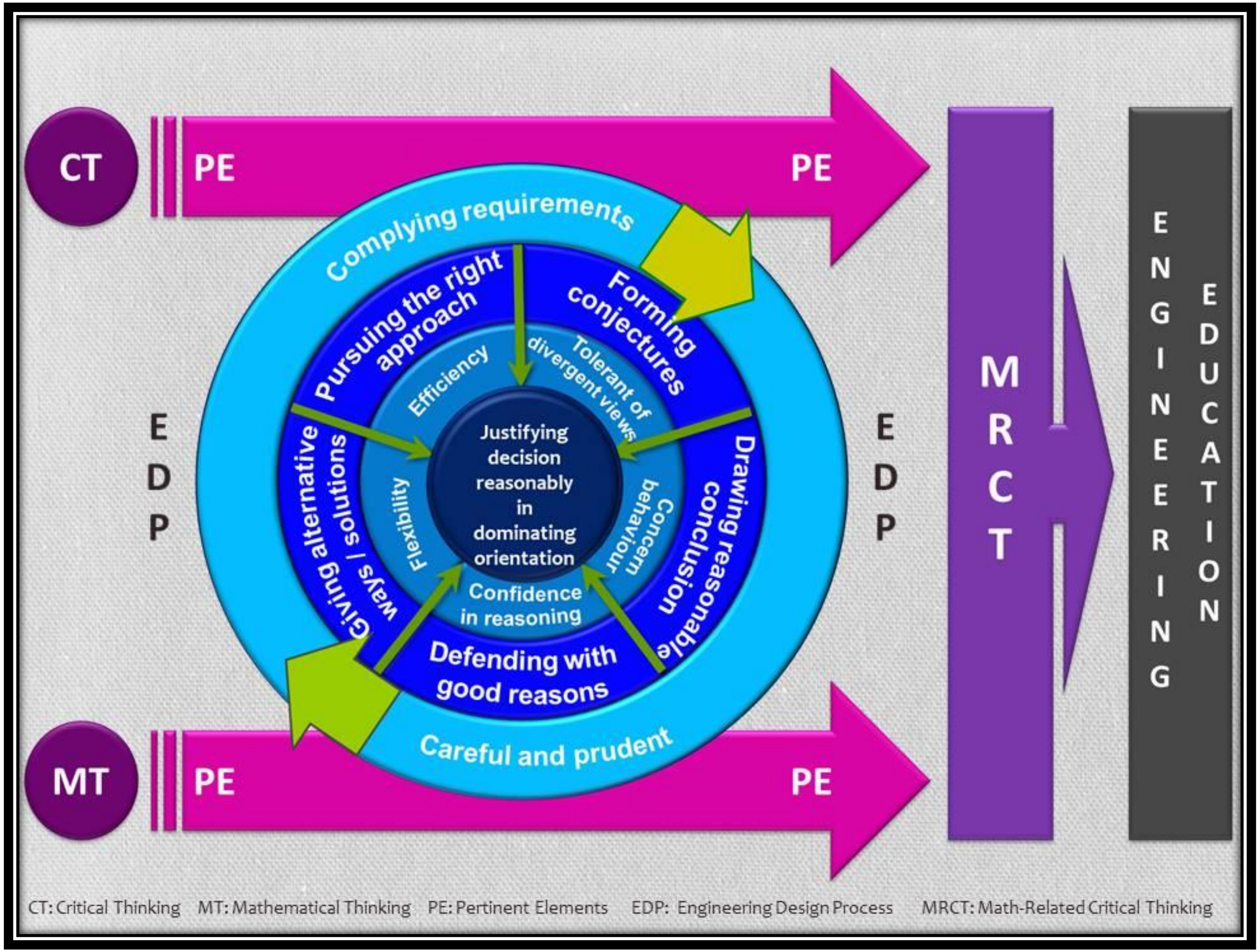


Figure 6.5: Emerging Theory in Relation to Engineering Education

6.3.1 MRCT for Civil Engineering Curriculum

As mentioned earlier, this study develops a substantive theory namely MRCT to provide useful information regarding the relation between critical thinking and mathematical thinking in real-world engineering practice. The information from MRCT helps the students understand the relevance of the skills with professional practice in solving complex engineering problem with regard to engineering design process. That is, the information appears to promote and widen students' horizon of understanding and seeing things. It may help to increase the quantity and quality of meaning that engineering students derive from what they read and perceive and that manifest in what they write, say and do.

In view of that, the researcher intends to promote the MRCT to the civil engineering curriculum, focusing mainly on integration of MRCT into the mathematics instruction for civil engineering students with some considerations as explained below.

Referring to academic curriculum about programme structure and course contents, and balanced curriculum, an engineering curriculum should provide students with ample opportunities for analytical, critical, constructive, and creative thinking, and evidence-based decision making and sufficient elements for training students in rational thinking (EAC-BEM, 2012).

Also mentioned in program outcomes (EAC-BEM, 2012) and student outcomes (ABET, 2014) that students of an engineering programme are expected to know and be able to perform or attain by the time of graduation several attributes, such as : i) An ability to apply knowledge of mathematics, science, engineering fundamentals and an engineering specialisation to the solution of complex engineering problems; ii) An ability to identify, formulate, research literature and analyse complex engineering problems reaching substantiated conclusions using first principles of mathematics, natural sciences and engineering sciences; and iii) An ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

Thus, besides knowledge of mathematics, science and engineering, the engineering curriculum should also provide skills like analytical, critical and creative thinking to students. In fact, every subject the students learn is a mode of thinking because only through thinking it could be understood (Paul, 2004). For example, knowing mathematics is not when able to recite mathematical formulas but when can think mathematically.

Moreover, ability to solve problems in mathematics through differential equations and apply this knowledge to the solution of engineering problems is one of the twenty-four outcomes that need to be fulfilled by an engineer before entering into the practice of civil engineering at the professional level (BOK2 ASCE, 2008).

"*Mathematics helps engineers in forming, analyzing, and optimizing the functionality of the phenomena, in order to design and develop a system. Mathematics enhances the ability of students to engage in abstract thinking and it also arouses their imagination. An innovative engineer is the one who is creative; and creativity comes from good imagination and abstract thinking. Therefore, a successful innovative engineer is the one who most likely equipped himself/herself with substantial knowledge of mathematics*" (Moussavi, 1998, p.2)

"Critical thinking is the art of thinking about thinking with a view to improving it. Critical thinkers seek to improve thinking, in three interrelated phases. They analyze thinking. They assess thinking and they up-grade thinking (as a result). Creative thinking is the work of the third phase, that of replacing weak thinking with strong thinking, or strong thinking with stronger thinking. Creative thinking is a natural by-product of critical thinking, precisely because analyzing and assessing thinking enables one to raise it to a higher level. New and better thinking is the by-product of healthy critical thought." (Paul, 2004)

Therefore, it is seen that mathematics is a potential medium to enhance the ability of students to engage in critical thinking and mathematical thinking through mathematical problem solving (Moussavi, 1998) in order to form the thinking to be creative and innovative (Moussavi, 1998; Paul, 2004). This ability is promising in forming a successful innovative engineer with new and better thinking.

Accordingly, a schematic diagram is proposed as in Figure 6.6 to illustrate the role of MRCT in civil engineering instructions. MRCT is infused into the instructions of engineering mathematics (EM) and other civil engineering (CE) subjects.

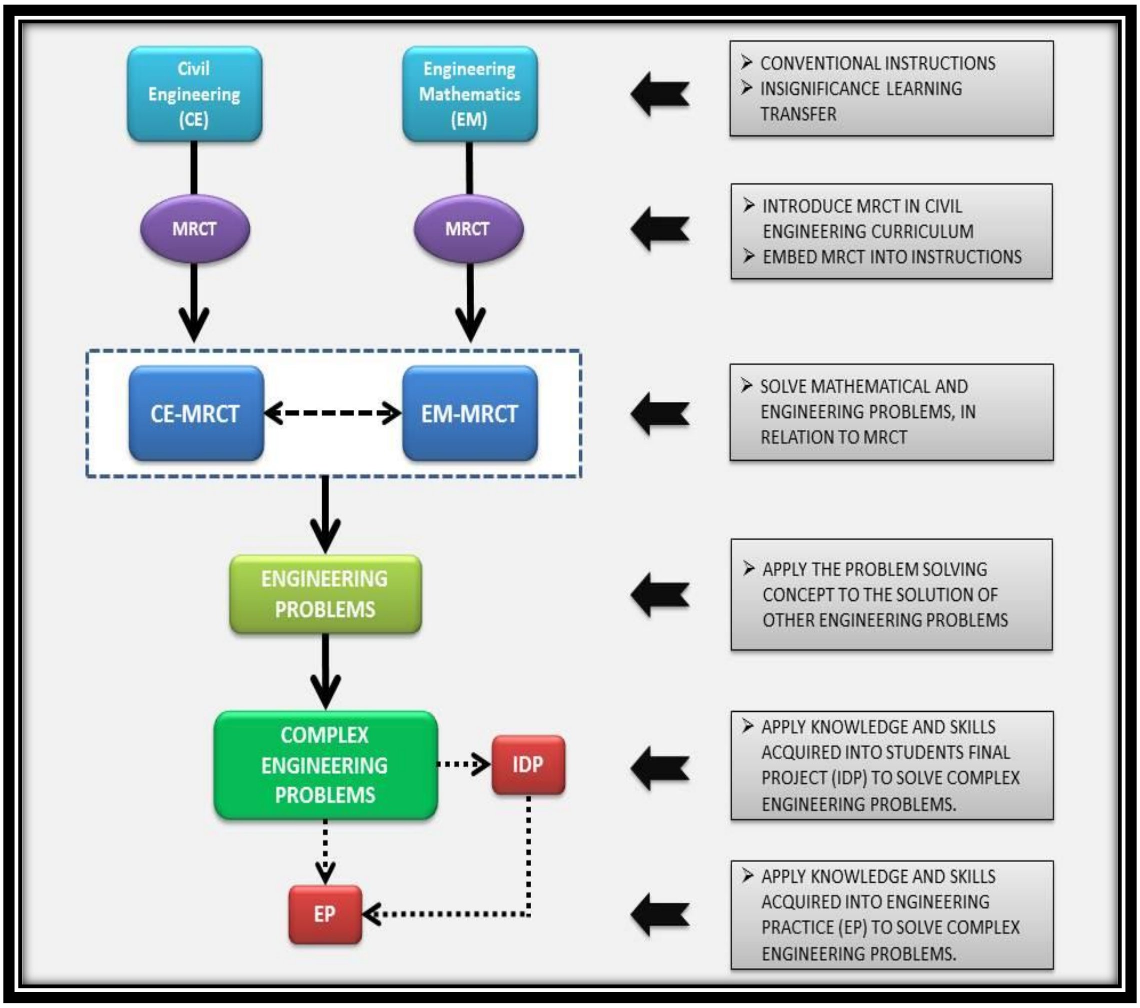


Figure 6.6: Schematic Diagram Showing the Role of MRCT in Civil Engineering Instructions

Conventional instructions are too specific-domain and thus, might have caused an insignificance learning transfer. Introducing MRCT in civil engineering curriculum shall provide students with ample opportunities to understand and acquire basic principles and skills of the discipline. Embedding MRCT into the instructions allows its integration across the curriculum and for that, the prescribed content materials in conventional instructions need to be restructured. The curriculum shall also be balanced and includes the pertinent technical and non-technical attributes aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council.

In view of that, students of civil engineering programme that would be treated with these MRCT-embedded instructions are expected to be able: i) to solve mathematical and engineering problems in relation to MRCT; ii) to apply the problem solving concept to the solution of other engineering problems across the engineering courses; and iii) to apply knowledge and skills acquired into the final project (IDP) and eventually into engineering practice to solve complex engineering problems.

For that reason, the students' final project namely Integrated Design Project (IDP) should provide students with opportunities to apply knowledge and skills acquired throughout the engineering program into real-world engineering problems. MRCT has revealed that making decision was a prominent process occurred at all stages of design process in real-world engineering practice, together with six essential processes as action and interaction in justifying decision. Thus, the IDP can be tailored to expose and familiarize students to the real-world engineering experiences by allowing students to apply MRCT in facilitating the problem solving process. Real engineering problems are often ill-structured and hence, exposing students to such real problems during IDP equips them with skills and experience to solve complex engineering problems in real-world engineering practice.

Additionally, by recognizing the role of MRCT in engineering design process may help engineering educators to better guide students how to engage in MRCT and transfer the knowledge material they have learned across the engineering courses into engineering practice. It serves platform for the students to develop thinking to a higher level to be creative and innovative to be able to solve complex engineering problems.

The propose recommendations for integrating MRCT into the teaching of engineering mathematics and other civil engineering subjects might face some significant challenges from faculty members who are not convinced of the need to change the conventional style of teaching. However, it is believed that the MRCT able to spark an initial trigger for a new turn of emphases on instructional approaches.

6.4 Conclusions

This study had set a dual grand goal: to produce a substantive theory related to interaction among pertinent elements of critical thinking and mathematical thinking in real-world civil engineering practice; and to transform the theory into integrative diagrams as alternative models in order to promote further understanding of the interaction and its implications for the engineering education. The study commenced with three research questions: what are the pertinent elements of critical thinking and mathematical thinking used by practicing civil engineers in engineering design process; how do the pertinent elements of critical thinking and mathematical thinking used in engineering design process interrelate among each other; and how do the pertinent elements of critical thinking and mathematical thinking used in engineering design process interact? Grounded theory methodology was applied in this research. Through the systematic coding process in grounded theory analysis, the research questions were answered.

The first research question was tackled in open coding where the pertinent elements of critical thinking and mathematical thinking were identified. The second question was addressed to axial coding and by using the Conditional Relationship Guide, the interrelation among the pertinent elements was developed. During selective coding, the interrelated pertinent elements were correspondingly integrated to have insight into the interaction among the pertinent elements. Through this selective coding the third research question was answered. While having three parts of question, the answers for the questions are not distinct and separated but closely related and interwoven, as discussed in Section 6.2.1. Ultimately, this study developed a substantive theory that revealing insight into the interaction among pertinent elements of critical thinking and mathematical thinking in the real-world civil engineering practice. This substantive theory namely Math-Related Critical Thinking (MRCT) explains about the interaction between critical thinking and mathematical thinking in the real-world civil engineering practice. It is a process theory of justifying decision reasonably in dominating orientation, in engineering design process.

The relations between the MRCT and theoretical literature, and its implications to engineering education, have been comprehensively discussed in the previous sections. This final section condenses the concepts discussed in preceding sections and chapters, but it does not intend to repeat previous discussions; rather, it concentrates on conclusions and implications arising from the study. Therefore, this section focuses on the limitations of the study, recommendations for future research and summary of the research contributions.

6.4.1 Limitations

Section 1.8 outlined the major delimitations of the research. Important considerations in this study were related to the scope of engineering investigated and the background and professionalism of the informants. The scope of engineering investigated was the real-world practice of civil engineering, focusing on the engineering design process. Two civil engineering consultancy firms in the southern region of West Malaysia were involved in this study. A total of eight practicing engineers were interviewed as informants for this research. The engineers have had at least five years' experience in the field of civil engineering design. The data collected from the interviews were limited to the informants' willingness and capacity to recall and depict their experiences throughout the interview sessions.

Within this context, this section lists the limitations of the study identified that may benefit the future research:

Firstly, since this is a benchmark study of having insight into the interaction among pertinent elements of critical thinking and mathematical thinking in civil engineering practice, the scope of engineering investigated was confined to the engineering design process. Therefore, the informants were homogeneous and purposefully selected for fulfilling the delimiting criteria of this study.

Secondly, the emerging theory was based on the researcher's theoretical sensitivity, reflexivity and plausible interpretations through the lens of the informants and grounded theory analysis. Thus, the theory is provisional, dependent on context, never completely final, and always subject to negotiation based on further context. In view of that, the theory is deemed necessary for further refinement and advancement.

Thirdly, as the study focused in understanding the interaction among pertinent elements of critical thinking and mathematical thinking in engineering design process in civil engineering practice, no claim was made regarding generalisability to other engineering design. The theory was developed for a better understanding of the main concerns encountered in its substantive area, from the particular perspective of the researcher only. Nevertheless, the substantive theory is considered transferable to contexts of other engineering design that are comparable to the context under study.

6.4.2 Further Research

This study may inform not only engineering education, engineering educators, engineering students and practicing engineers, but also future researchers who are interested to further investigate the application and interaction of critical thinking and mathematical thinking in real-world engineering practice. A theoretical position is provisional and proposes a foundation to begin further research. This study has developed a substantive theory which provides an insight into the interaction among pertinent elements of critical thinking and mathematical thinking in real-world civil engineering practice. The theory offers useful information to engineering education; yet, capitalising on that information seems elusive.

One way of addressing this issue is by making sense of the theory through further research in engineering practice and infusion of the theory into the engineering curriculum. Accordingly, this study contributes to future research by suggesting potential research themes and providing some comments regarding the use of the method.

6.4.2.1 Potential Research Themes

As this study is a benchmark for having insights into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in the engineering practice, more research must be done to more fully understand the interaction in the context of engineering design. This study provides insights that form an essential foundation for the design of a study to further investigate and strengthen the substantive theory developed in this study. The new study could test the substantive theory for conditions in which it applies with a larger population of informants based on the criteria, methodology, and findings of this study.

A longitudinal study should be conducted to provide richer information to engineering community. The study may incorporate the methodology and further investigating the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world civil engineering practice. It also includes an investigation of interrelation and interaction of pertinent elements at each stage of design process. This is to have better and deeper insights into the role of these two types of thinking in engineering design process.

Two main areas need to be focused from the perspective of the researcher; scope of engineering practice and informants for the study. In the context of engineering practice, the scope must cover not only the design process but also the direct or indirect involvement of the design team in supervising, monitoring and troubleshooting projects at the construction sites. For informants, a heterogeneous sampling should be performed, and perhaps design supporting team should also participate such as draftsman, site engineers, site supervisors and technical assistants, so that, more information could be contributed to engineering education community.

A following new research can investigate an infusion of the substantive theory into the engineering education, particularly in civil engineering curriculum. The instructions of mathematics and engineering subjects need to be restructured to embed the substantive theory, in order to be more balance, practical and deliverable for engineering students. To access the utility of this theory infusion, a preliminary study should be conducted to elicit engineering educators' initial responses to the implementation.

This new research would provide views on issues such as: how to fit best the theory into the instructions? What are barriers to infusing the theory into the instructions? How to measure the impact of the implementation? This study may use a verbal protocol analysis, possibly with a pre- and post-test to investigate the presence and changes of critical thinking and mathematical thinking of engineering students as a result of the theory infusion.

Additionally, grounded theory methodology can be used to identify and to understand particular factors influencing students' changes and achievement. Conducting this new research would provide valuable insights into understanding the challenges and impacts in translating and addressing the research finding to learning and teaching practice.

6.4.2.2 Comments on Methodology for Future Research

This study used grounded theory as the research method by adopting the Strauss and Corbin's version of grounded theory. Nevertheless, the version was not entirely adopted as a whole. The method was partly modified after considering several aspects related to the appropriateness of answering the research questions as explained in Section 2.6 but still preserving the basic tenet of the methodology. The real essence of grounded theory is the ability to view a phenomenon from the lens of informants and retell the story of the phenomenon as a set of theoretical position in a form of substantive theory. Regardless of what version of grounded theory is used, it is time consuming, effort demanding and tedious. However the process involved in the research rewarded the researcher with deep understanding of the method. The lessons learned throughout the process of doing grounded theory research can contribute to the future researchers contemplating grounded theory as a potential research method. These lessons are presented as the following guidelines:

1. **Transcribing**. Transcribe each interview before doing the next one. Even though manually transcribing consumes a lot of time, there are positive returns to all the time spent. Manually transcribing helps a researcher to figure out the whole ideas of the interview and decide how to sample for the subsequent theoretical sampling. Since grounded theory is a fraction of qualitative research, it is quite unethical to ask someone else who is not part of research team to listen to the recording or to read the transcript. Besides losing chances to capture the whole ideas of the interview during transcribing, it is undermining anonymity. Analyze the transcript before initiating the subsequent interview and for that purpose, the transcript is now subjected to coding process.

2. **Coding**. Code each interview transcript before conducting the next interview. It is important for theoretical sampling and to prevent data overwhelm. Read the previous analyzed transcripts before doing new transcript analysis for better comparison in performing constant comparative method. It is only through reading and reading the transcripts reveals those little nuances that help to adapt to future interviews, and also identify where the research is in need. It might very difficult to analyze the data without any software especially when having time constraints. However, if the main aim is to experience the real value of doing grounded theory, the researcher personally does not recommend using any qualitative data analysis software. Let theoretical sensitivity together with comparison method immerse a researcher in the data to be more creative and having clearer sense of what is actually going on. It is important to remember that coding in grounded theory is not

the same as coding in other qualitative methods. There is nothing wrong with discussing data with peers and supervisors, and even share memos as grounded theory is an experiential process. However, the process of coding proceeds differently in grounded theory analysis, starting with first data acquisition, which in itself gives a sense that the coder needs to be the researcher. The effort and time to be put into learning the software can now be put into data acquisition, analysis and memoing.

3. **Memoing.** Write memo as much as possible to capture ideas and to describe thoughts and process throughout the study using grounded theory method. Memoing acts like a lubricant to push a research forward and helps a researcher to see connections within and between data. The more memos are written, the smoother the flow of data acquisition and analysis process.

4. **Go with the flow.** Many doctoral researchers have dilemma to do intense literature review in preparing a thesis proposal. Having this literature review at the early stage of a research is not recommended in doing grounded theory. Whilst, it is important to meet the requirements of the university while being faithful to the methodology and of course it is challenging. Yet, in the opinion of the researcher based on this study, it is better to go with the flow and to the extent possible, harmonize the methodology and the university requirements in moderation and with conscious considerations. Do the literature review and whenever possible, minimize preconception when doing data acquisition and analysis. After all, after getting the doctoral degree, the grounded theory can be followed more closely.

6.4.3 Summary of Research Contributions

The results of this grounded theory study are expressed as a substantive theory, that is, as a set of pertinent elements of critical thinking and mathematical thinking that are interrelated to one another in a cohesive whole. As described in Chapter 1, the prime goal of this study was to develop a substantive theory pertaining to critical thinking and mathematical thinking. Complementing to this goal, the emerging theory was transformed into integrative diagrams as alternative models to promote further understanding of the interaction among the pertinent elements and its implications for the engineering education.

The interrelation and interaction among the pertinent elements were depicted in *Figure 5.4: Interrelation and Interaction among Pertinent Elements of Critical Thinking and Mathematical Thinking* and *Figure 6.3: The Relation between Critical Thinking and Mathematical Thinking Based on the Emerging Theory and a Synthesis of Literature*. The key features of the story line were portrayed in a conditional matrix, as shown in *Figure 5.5*. More importantly, *Figure 6.5: Emerging Theory in Relation to Engineering Education* represents the process journey of this study starting from the initial exploration to identify pertinent elements of critical and mathematical thinking, followed by the development of the process theory in the form of conditional matrix, then the development of the substantive theory namely MRCT and ended by showing the orientation of the theory towards engineering education. Whereas, the implications of the substantive theory for engineering education were translated to the integrative diagram in *Figure 6.6: Schematic Diagram Showing the Role of MRCT in Civil Engineering Instructions.*

To conclude this thesis, the main contributions of the study are presented as follows:

1. **Engineering education** – This study contributes to engineering education body of knowledge by providing useful empirical information for engineering curriculum, educators and students. The substantive theory developed in this study provides evidence that pertinent elements of both critical thinking and mathematical thinking were used and interwoven throughout the engineering design process. This understanding of interrelation and interaction among the pertinent elements shall be infused in mathematical problem solving activities in nurturing engineering students with real-world engineering application.

   The information from the substantive theory helps the students understand the importance and relevance of the thinking skills with professional practice in solving complex engineering problem with regard to engineering design process. This might help the engineering educators to strengthen engineering instructions by having an engineering curriculum that more closely represents the real engineering practice. The information regarding the usage of both thinking in the real-world engineering practice is still found wanting in relation to its importance in engineering education.

Therefore, this study, to the researcher's best knowledge, has contributed by presenting for the first time in engineering education the substantive theory which relates both critical thinking and mathematical thinking used by the engineers in real-world engineering practice.

2. **Literature.** This study contributes to the extant literature by presenting a different perspective of critical thinking and mathematical thinking from real-world engineering practice, proposing a substantive theory that explains the interaction between these two types of thinking. This contribution is seemed necessary since hardly to find in the literature comprehensive studies that relate critical thinking to mathematical thinking in the context of engineering. Moreover, to the researcher's best knowledge, there is no theory available that explains interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in real-world engineering practice for engineering education. This is somewhat quite alarming to its perceived importance.

3. **Integrative Diagrams**. The interrelation and interaction among pertinent elements explained in the story line of the substantive theory were transformed into integrative diagrams. This transformation contributes alternative models to promote further understanding of the interaction among the pertinent elements and its implications for the engineering education. The diagrams helped to make the grounded connection among the pertinent elements explicit to the reader.

4. **Empirical Research.** This study offered a good opportunity to access vital insights into an area of research lacking in theoretical development work and in empirical research. This study contributes to theory development by presenting a substantive theory of Math-Related Critical Thinking which

revealing insight into the interaction among the pertinent elements of critical thinking and mathematical thinking. Many educational research have been done in the context of engineering; yet, the educational research in the real-world engineering practice is still found wanting.

In view of that, this study contributes to expand the research horizon of critical thinking and mathematical thinking in engineering practice for engineering education. By considering the research limitations (see Section 6.4.1); this study contributes to future empirical research by enabling the formulation of further research questions and the determination of focus research area.

5. **Methodology** - This study presented an opportunity to contribute to engineering education research methodology by providing a set of propositions for further study and expansion. Accordingly, the research approach used in this study serves a platform for its further refinement and adaptation in the context of educational research in engineering. This study contributes evidence in support of grounded theory as a useful research methodology to investigate and study phenomena in engineering world. Grounded theory has been a non-preferable choice of methodology in the context of engineering research and this study might provide a different perspective on this situation.

Ultimately, for concluding remarks; *the engineers used their minds in performing design process while the researcher used her brain to capture the process from the lens of the engineers, using grounded theory methodology for having insights into Math-Related Critical Thinking in real-world civil engineering practice, in relation to engineering education.*

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Appendix A: E-Mail Conversations

Sharifah Shar <sharifah8283@gmail.com>

Mathematical Thinking

5 messages

sharifah <sharifah8283@gmail.com> Tue, Oct 28, 2014 at 8:24 PM
To: alans@berkeley.edu

Dear Prof. Alan,

I humbly introduce myself as Sharifah, a PhD student from Malaysia.
I am currently doing research in engineering education regarding the mathematical thinking.
I really appreciate if you could help me in giving your precious opinion regarding the above matter I used in my study, and for that, my truly grateful thanks for your kindness.

I've read your books on 'Learning To Think Mathematically (1992)' and 'How We Think (2010)' and I've a question here :
If in my study i would like to find out what are the elements of mathematical thinking involve in carrying out a task, which 'model' of your mathematical thinking suits best my study if interviewing is the method used for collecting data?

Your kind reply is highly appreciated. Thank you.

Alan Schoenfeld <alans@berkeley.edu> Fri, Oct 31, 2014 at 11:07 AM
To: sharifah <sharifah8283@gmail.com>
Cc: Alan Schoenfeld <alans@berkeley.edu>

If you are trying to understand why someone did what they did while working on a task, then the interview priotocol I find most useful is to

- have them solve the task out loud, with minimal intervention, while you videotape the attempt;
- ask them to tell you what they think was interesting or important;
- have them watch the videotape and comment on what they did;
- ask your own questions about what you think was interesting or important at various points in the videotape.

Alan Schoenfeld
alans@berkeley.edu

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sharifah <sharifah8283@gmail.com> Fri, Oct 31, 2014 at 11:49AM
To: Alan Schoenfeld <alans@berkeley.edu>

My most grateful thanks for your kind reply.

I appreciate your further help and precious opinion.

In my study, the participants are professional engineers.
I would like to find out what are elements of mathematical thinking being used in their engineering design practices.
After identifying the elements, I will use a qualitative research design to explain the 'grounded' interaction between these elements with the design process.

I appreciate the task out loud but i don't think it's suitable to be carried out on my participants (professional engineers).
So, i plan to use interview protocol to have them telling me their experience in carrying out their tasks.
From the interviews transcription, I will have to 'identify' what are elements of mathematical thinking being used.

My questions here:
Can I used your five aspects of mathematical thinking (resources, heuristics, monitoring & control, belief & affect, and mathematical practices) for that purpose of my study?
From my understanding, it's a framework of mathematical thinking (Schoenfeld, 1992) in relation to problem solving, metacognition and sense-making in mathematics. So, is it competent if using the framework as the guide to identify elements of mathematical thinking in their practices?

I really appreciate your kind reply Prof. Alan. Thank you.

Alan Schoenfeld <alans@berkeley.edu> Fri, Oct 31, 2014 at 12:18 PM
To: sharifah <sharifah8283@gmail.com>
Cc: Alan Schoenfeld <alans@berkeley.edu>

Specific answer: yes, the frame from the 1992 paper is appropriate.

-Alan Schoenfeld
[Quoted text hidden]
Alan Schoenfeld
alans@berkeley.edu

Appendix B: Interview Protocol

Topic: Math-Related Critical Thinking (MRCT) in Real-World Civil Engineering Practice in Relation to Engineering Education

Introductory Protocol

For the purpose of data collection, I would like to audio tape our conversations. For your information, only personnel directly involved in my research will be privy to the tapes which will eventually be destroyed after they are transcribed. In addition, please sign a consent form devised to meet our human subject requirements. Essentially, this document states that:

(1) All information will be held confidential
(2) Your participation is voluntary and you may stop at any time if you feel uncomfortable
(3) No intention to inflict any harm.

Thank you for agreeing to participate.

I have planned this interview to last no longer than two hours. During this time, I have several questions that I would like to cover. If time begins to run short, it may be necessary to interrupt you in order to push ahead and complete this line of questioning.

Introduction

You have been selected for the interview today because you have been identified as someone who has a great deal to share about your experiences in executing civil engineering practices. My research project focuses on the nature of interaction between critical thinking and mathematical thinking in the civil engineering practices, with particular interest in understanding how these two types of thinking relate, interact and integrate during the execution of civil engineering practices. However rest assured that my study does not aim to evaluate your techniques or experiences. Rather, I am trying to learn and understand more about the aspects of critical thinking and mathematical thinking used by practicing civil engineers. Hopefully the research findings will reveal some useful information to the engineering program outcomes and engineering education, in cultivating the prospective civil engineers with real practices-oriented Math-Related Critical Thinking.

For your information, the subsequent interviews with you might be appropriately conducted based on the earlier findings and you will be informed accordingly.

Interview Questions

Information on the highlighted items is to be gathered by asking the following:

Current Job.
What is your present position in this company?
What are your major responsibilities?
How long have you held this position? How many projects have you had under your supervision?
What do you enjoy about your job?
What are the challenges you face?

Design Process.
What kind of engineering design is your company engaged in?
Can you please explain to me how many stages of process in engineering design?
How to ensure everyone is following the same procedure?
Which stages are considered critical from your point of view?
Why the stages are considered critical from your point of view?
What are the skills required in performing the tasks?
Why are these skills important?
How those skills contribute in solving complex engineering problem?
What factors would help you identify a problem?
Can you share with me your experience, solving a complex engineering problem?
Over the next ten years, what do you see as the key changes in the civil engineering activities?

Critical Thinking.
What are your opinions about the use of critical thinking skills in design process?
Referring to the design process, where do you apply the skills the most?
How do you apply the skills?
What do you do to acquire these skills?
What do you do to sharpen these skills?
What are the attributes that an engineer should have in order to acquire those skills?
Do you think it is important for an engineer to have such attributes?
Why do you think it is important for an engineer to have such attributes?
How do these skills contribute to solve complex engineering problem?
How do these skills affect work performance?
How to ensure the continuous of the application of the skills among civil engineers?

Mathematical Thinking.
What are your opinions about the use of mathematical thinking in design process?
Referring to the design process, where do you think you will use mathematics the most?
How do you apply mathematics in design process?
How does mathematical thinking contribute to solve complex engineering problem?
Can you explain to me some examples of this information?
What kind of mathematical techniques would help you in identifying and analysing complex problems?
If you were given a chance to re-schedule civil engineering program in order to meet the required attributes of an engineer, what changes would you like to make?
Why do you want to make such changes?

Others. Thinking back over your remarks
Anything else of importance you would like to add?
Anything else we did not talk about that appears relevant?
Any comments you would like to make regarding the discussion?

Appendix C: Associate Elements

Open Codes	Category Name
Applying knowledge / experience	Knowledge /experience transfer
Following design process Following codes of practice Creating / solving problem	Nature of practices / Adherence to standard / Discipline
Design team members; Authorities Client/ contractor / architect	Communication
Specialization; Coordination Consultant / colleague/ contractor	Team work / symbiosis
All angles of view	Lateral thinking
Preliminary stage Designing stage	Cyclic / Repetitive process
Interest; Patience; Independent; persistence; initiative; confidence; Satisfaction	Personal attributes for designing
Facilitates designing; Accelerating works	Engineering software / Computer proficiency / Meeting deadlines
Projects Experience Problems	Unique
Technical background Theory Confidence Good rapport	Factors for getting approval
Prioritize Safety Minimize Cost	Factors in considering design / Task of an engineer
Theory Experience	Designing skills
Authority Client Line of communication	Identifying problem
Dealing with authority a) Presenting theory and technical b) Relationship Approaching techniques / Contact ; material defect and expertise Rapport Experience	Things to bring forward from past projects
Acquiring knowledge Endorsing / approving Executing tasks Sense of belonging	Responsibility

Appendix C: Associate Elements - continue

Open Codes	**Category Name**
Direct from developer From architect (group consultant) From contractor	Method of appointment / Job awarded
Changes from owner Repeating design process Resubmission Getting plan endorsement	Matters during / after submission
Design stage Modelling stage	Engineering sense
Pre-consult>submit> online submission Hardcopy submission Online submission >hardcopy submission	Online submission requirements
Beginning – need statement determines concept layout / design concept	Critical stage
Design stage Constraint : to meet deadlines;- Waiting for authorities approval Meeting client deadlines Re-designing Re-submit Waiting for approval	longest stage (another cyclic)
Imagination Own creativity Engineering sense	Modelling design
Implicit Indirect Embedded	Mathematics /formula usage
By task – not synchronize By project -smoother	Design tasks distribution
Survey plan Site plan	Infra needs
Communication Experience Theory/knowledge	Important aspects in designing

Appendix D: Interview Consent Form

Research Project Title: **MATH-RELATED CRITICAL THINKING (MRCT) IN REAL-WORLD CIVIL ENGINEERING PRACTICE IN RELATION TO ENGINEERING EDUCATION**

As part of the requirements for my doctoral research study at UTM Johor Bahru, I have to carry out an educational research in the context of engineering. My research is being supervised by three professional experts from UTM; Prof. Dr. Shahrin bin Mohammad, Prof. Dr. Mohd Salleh bin Abu and Dr. Mahani binti Mokhtar.

You have been selected to participate in my study because you have been identified as someone who has a great deal to share about your experiences in executing civil engineering practices. Please take your time to review this consent form and discuss with me any questions you may have, or words you do not clearly understand. You may take your time to make your decision about participating in this study and you may discuss it with your friends or family before you make your decision.

Purpose of the Study

My research project focuses on the nature of interaction between critical thinking and mathematical thinking in the civil engineering practices, with particular interest in understanding how these two types of thinking relate, interact and integrate during the execution of civil engineering practices. However, rest assured that my study does not aim to evaluate your techniques or experiences. Rather, I am trying to learn and understand more about the aspects of critical thinking and mathematical thinking used by practicing civil engineers.

Study Procedures

This study involves two ways of interviewing individuals. First, I will conduct individual interview sessions and ask questions about your experiences in executing civil engineering tasks, particularly about the engineering design.

Second, I will conduct a focus group discussion whereby a group of people will be asked questions about experiences in executing civil engineering tasks, particularly those which are related to engineering design. The interviews and focus groups will take place in the office at your workplace or any other appropriate places, as you prefer. You will have the option to participate in a one-on-one interview, in a focus group, or in both.

For the purpose of data collection, I would like to audio tape our conversations. For your information, only personnel directly involved in my research will be privy to the tapes which will be eventually destroyed after they are transcribed. All information you provide will be kept strictly confidential and will only be used for the purpose and in the context of this research study.

For your information, the subsequent interviews might be appropriately conducted based on the earlier findings. I will ask if you would be willing to be contacted at a later date in case we need to clarify any of the responses given in the interview. This would involve providing your name, address, and phone number. All personal information you provide will be kept strictly confidential, separate from the interview data and kept on file for the duration of the study. At the conclusion of this research project I will destroy all computer and paper records containing your identifying information. Access to personal information will be restricted to the research team only and will be secured electronically and physically in a locked office away from public access.

Participant's Initials _________

I have planned this interview to last no longer than two hours. During this time, I have several questions that I would like to cover. If time begins to run short, it may be necessary to interrupt you in order to push ahead and complete this line of questioning. You may stop at any time if you feel uncomfortable.

Risks and Discomforts

I will make every effort to make certain that there will be no way that people can identify you in the study. However, I cannot guarantee you absolute confidentiality.

Costs

The study procedures are conducted at no cost to you.

Benefits

There may or may not be direct benefit to you from participating in this study. Hopefully the research findings will reveal some useful information to the engineering program outcomes and engineering education, in cultivating the prospective civil engineers with real practices-oriented Math-Related Critical Thinking.

Confidentiality

Information gathered in this research study will appear in the thesis and may be published or presented in public forums; however, your name or other identifying information will not be used or revealed. Pseudonyms will be used in my report to ensure anonymity of your personal details. Despite all efforts to keep information shared in the focus groups confidential, there is a chance that a focus group participant may share the information they have heard. I therefore cannot guarantee absolute confidentiality.

Voluntary Participation/Withdrawal from the Study

Your participation in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time.

Questions

You are free to ask any questions that you may have about your rights as a research participant. If any questions come up during or after the study, you can contact me at any time as you wish.

Participant's Initials _________

STATEMENT OF CONSENT

Participant:
I have read this consent form. I have had the opportunity to discuss this research study with the researcher. I have had my questions answered by her in the language I understand. The risk and benefits have been explained to me. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this study is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study. I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed.

I………………………………………………………………………………agree to participate in this research study.

The purpose and nature of the study has been explained to me in writing.

I am participating voluntarily.

I give permission for my interview to be tape-recorded.

I understand that I can withdraw from the study, without repercussions, at anytime, whether before it starts or while I am participating.

I understand that anonymity will be ensured in the write-up by disguising my identity.

I understand that disguised extracts from my interview may be quoted in the thesis and any subsequent publications if I give permission below:

(Please tick one box:)
I agree to quotation/publication of extracts from my interview ☐
I do not agree to quotation/publication of extracts from my interview ☐

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

Participant Signature: ________________________________Date: _____________________

Participant Name: ____

Participant Contact Number : ___________________(office) __________________ (mobile)

Participant Address (if consented to provide) ____________________________________

____

Researcher:
I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believed that the participant has understood and has knowingly given his/her consent.
Name: ____Date: ______________________

Signature: __________________________________Contact Number : ____________________

Participant's Initials _________

Appendix E: Conditional Relationship Guide

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
Applying / transferring maths knowledge / theory	Software is indeed a need; nevertheless, knowledge and theory we learnt during our study in university is also actually being applied, as it is being used in the software in the simplified form. So, the software just facilitates our job.	Design stage	Cognitive resources	Having mathematical views and sense-making; Adapting new approach	Using formula; Manipulating equation;	Selecting the right approach; Maths consciousness
Assessing credibility of output/info	Before producing the drawing, we will go through the output again, for both structure and infra, at least we go through again to check whether ok or not, then only we proceed	Design stage; Preliminary stage	Evaluation	Reviewing; Anticipating the results; Forming conjecture	Checking thoroughly; Self-correcting; Comprehending; Examining info	Pursuing the right approach; Defending with good reason
Careful and prudent	…after that we will discuss with the boss, and if he also agrees, we will submit our view to the authorities and if it is rejected, then only we will submit the one that using computer.	Design stage	Maturity	Self-correction; Decision to be made along the way	Having discussion;	Diligence in seeking info; Concern behaviour

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Checking thoroughly	Depends on their confidence, sometimes they come and seek for some advices, but I ask them to sit down together and check thoroughly the design concept as I am more satisfied to supervise from the beginning and not only at the end of the project	Preliminary stage	Analysis	Concern behaviour Self-regulation	Having discussion confirming	Pursuing the right approach
Clarify meaning	At preliminary stage, after getting the architecture drawing, we have to study it and determine our layout structure	Preliminary stage	Interpretation	Diligence in seeking info	Coming to grips with uncertainty; Making conjectures	Concern behaviour in making decision
Coming to grip with uncertainties	…for SAJ, water supply and sewerage, it is challenging when having unexpected problem, such as blocking the existing pipe, so, we have to think of how to solve the problem, how to lay the pipe in order to have a good flow and we have to make suggestions	Preliminary stage; Design stage During constructions	Mathematical Practices	Concern behaviour in making decision; Consciousness in assessing material; Solving open ended problem	Examining ideas; Giving alternative solution	Selecting the right approach; Tolerant of divergent views; Decisions to be made along the way

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Complying	As long as we follow the specification, it means we are fulfilling their needs. If what we do is within specification, complete with its protection, we are freely to design without any problem.	Design stage; Preliminary stage	Self-reflection	Self-regulation; Careful and prudent	Conforming; Gathering relevant info; Correcting; confirming	Concern behaviour
Comprehending	When we want to design, we must aware of all the changes, and to understand the meaning of the changes	Design stage	Interpretation	Correcting Confirming	Gathering relevant info	Complying Clarify meaning
Concern behaviour in making decision	It is undoubtedly that using software is very helpful…..but then again, when thing becomes easier, we always tend to be negligent, and our negligence makes us forget to see all the miniscule detailing, and this is really alarming and we need to focus on it	Design stage	Monitoring and Control	Adapting to new approach; Self-consciousness; Tolerant of divergent view; Selecting/pursuing the right approaches	How efficient knowledge/experience is used; Checking thoroughly; Careful and prudent	Flexibility in considering alternatives; Self-regulation

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
Confidence in reasoning	We cannot neglect safety factors and related specifications in satisfying something, and at the same time, we must confident that the thing we are going to do is workable, and having confidence in our design.	Design stage	Confidence	Self- regulation	(safety factor) (workable) Counter checking; Confirming	Drawing reasonable conclusion
Confirming	There was a case, where, after the building was built, they found some cracks. We rechecking our design, running into software, and it was confirmed our mistake. We had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks.	During construction; Preliminary stage	Self-reflection	Detecting failure;	Reviewing; Having discussion; Examining info	Self-consciousness; Selecting the right approach

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Conforming	…also have its specifications in the BQ, as well as in the drawing. Meaning, it's within the specifications and does not deviate from what has been submitted.	Preliminary stage; Design stage	Monitoring and Control	Decision to be made along the way; Self- regulation	Selecting the right approach; Complying; Counter checking	Organized; How efficient knowledge/experience is used
Considering relevant info	Design is design, need is need, meaning, if client wants to save cost, we can consider the minimum design but still having buffer for safety factors	Design stage; Preliminary stage	Inference	Consciousness in assessing material; Assessing credibility of output	Defending claims mathematically; Defending with good reasons; Comprehending (software)	Selecting the right approach; Dominating orientation; Forming conjectures
Correcting / Self-correction	After calculating the water demand, we do design, and after designing, if realized that we have over designed it, we can reduce the size from the result obtained using software.	Design stage	Self-reflection	Seeking for the best info; Self -regulation	Having discussion; Counter-checking; Confirming	Careful and prudent; having confidence
Counter checking	Software is used for doing calculation but for simple calculation we do it manually. We counter-check its output and make adjustment according to the specification.	Design stage; During construction	Self-reflection	Concern behaviour; Conforming	Working backward; Looking for pattern; Checking thoroughly	Correcting; Selecting the right approach

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
	Thus, mathematical thinking is important in designing.					
Decision to be made along the way	Our concerns continue until all work at site is finished, and it's not only revising documentation, sometimes after tendering out, still have amendments to be done	Preliminary stage; Design stage; During construction	Monitoring and Control	Tolerant to divergent views	Amending; Revising; Working backward; Analytical reasoning	How efficient experience is used; Concern behaviour; Selecting the right approach
Defending claims mathematically	We cannot compromise on safety to save cost, we have our permissible limit, if the size of the beam really cannot be reduced, we have to defend it, and as an engineer, we indeed have to defend it.	Design stage	Mathematical Practices	Consciousness in assessing material; Detecting failure	Considering relevant info; Defending with good reasons	Having mathematical views and sense making
Defending with good reason	…for gaining experience, it takes some time, it is there but we have to find the data, and the data must be correct, our assumption also must be correct, then only our design will be	Design stage	Explanation	Solving open ended questions	Engineering sense; Diligency in seeking info; Defending claims mathematically; Confidence in reasoning	Drawing conclusion

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
	correct, and even later if it fails, it is not our faults but might be because of something else.					
Detecting failure	For senior engineers, those who ever did it manually, when it comes to software, they are more meticulous, they know where to check more detail, compared to those young engineers	Design stage; During construction	Analysis	Assessing credibility of output; Solving open ended problem	Checking thoroughly; Using evident to resolve problem;	How efficient knowledge/experience is used; Making conjectures
Diligence in seeking info	Sometimes asking the local people or the authorities about any new development there, if any, and the contractor also sometimes gives some info…	Preliminary stage	Orderliness	Gathering info / data/relevant info	Simulate real life experience; Having mathematical views and sense-making	Concern behaviour in making decision
Dominating orientation	…it does not involve the whole design, we will try our best to minimize the cost, and at the same time to make it workable	During construction; Design stage	Belief and Effect	Assessing credibility of output; Concern behaviour	Having discussion; Considering relevant info; Justifying reasonably; Adjusting; Having mathematical views and sense-making	Defending with good reasons; Self-regulation; Pursuing the right approach; Defending claim mathematically

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Drawing reasonable conclusion	For example, for installing a culvert at the place where the ground is not so strong, is it necessary to do piling for its foundation? After having discussion, we decided not to do it to let the culvert settle with minimum rate, because piling without doing grounding treatment for the road will make the culvert bulging and this will cause problem to the road users	Design stage	Inference	Forming conjectures;	Examining ideas Assessing credibility of statement Having discussion	Justifying reasons Having mathematical views and sense-making; Confidence in reasoning
Engineering sense	If we are designing a building, where to put its beams and columns, where are the best position for them, and at the same time we want to minimize the columns because we want to minimize its foundation. So, all this comes from our sense, our creativity	Design stage	Cognitive resources	Making conjectures; Anticipating the result	Considering relevant info; Intellectual curiosity; Imagining	Self-consciousness Confidence

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Examining Ideas / output	Usually, from the architecture drawing, we could see where the beam, column and slab are placed, and if the columns are having too big gap, we will ask permission from the architect to add some more columns, or otherwise the beam will be bigger.	Preliminary stage; Design stage	Analysis	Justifying Looking for patterns	Considering relevant info; Working backward Assessing credibility of statement Having discussion	Giving alternative solutions Drawing reasonable conclusion
Flexibility in considering alternatives	Sometimes what we design does not totally fit the real situation at site, or maybe difficult to execute, so, we have to think of other alternatives.	All stages	Truth seeking	Giving alternative ways; Concern behaviour	Making conjectures; Counter-checking; Selecting the right approach; Looking for pattern	Tolerant of other views

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Forming conjectures / assumption	For structure, we just enter into the software, but if it fails, we have to find out possible reason, maybe we have put too much loading, or have mistakenly doubled it, or maybe entered without loading, and one more thing, to look at its support direction, which all these could be factors of failure of a design for certain beams, slabs or columns.	Preliminary stage; Design stage	Mathematical Practices; Inference	Coming to grips with uncertainty Tolerant of divergent views; Concern behaviour in making decision; Justifying reasons	Simulate real life experience; Considering relevant info; Flexibility in considering alternative; Having mathematical views and sense-making	Defending claims mathematically; Giving alternative solutions
Gathering info / data/relevant info	Either directly under contractor, architect or developer, the flow of work remains the same, meaning, we know our scope of work and we will gather information. …. If we got comments from the authorities, such as, have to widen the drain or insufficient pond, then, we gather all the comments and forward to planner	Preliminary stage; Design stage	Heuristics	Revising; Amending	Comprehending; Seeking relevant info	Complying

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
Giving alternative ways / solutions	Usually we have to check it one by one, perhaps, some of the things we apply to the drawing is unnecessary, and maybe we can do it another way…	Preliminary stage; Design stage	Belief and Effect	Coming to grips with uncertainty	Simulate real life experience; Forming conjectures; Checking thoroughly; Diligence in seeking info	Flexibility in considering alternatives
Having discussion	…we have to know all, cannot miss any data, and must have sufficient data, and all this is done in a team, having discussion, again and again….	Preliminary stage; Design stage	Monitoring and Control	Assessing credibility of statement; Concern behaviour	Selecting/pursuing the right approach; Applying suggestions by others	Confidence in reasoning
Having mathematical views and sense-making	Sometimes, when having high safety factor, columns and beams become bigger, in fact, if manually done, they can be smaller, can save cost, and clients also happy can save their money. We follow a rule of thumb, if for column will be 6%, and if for IWK, usually will be based on unit, but, if we based on area, we already have our own table, so, we can estimate it.	Preliminary stage; Design stage; During construction	Mathematical Practices	Assessing credibility of output; Justifying; Forming conjectures; Solving open ended problem; Applying theory; Mathematical proficiency	Cross checking; Modifying; Checking thoroughly; Confidence; Using formula; Manipulating data;	Mathematical proficiency; How efficient knowledge/experience is used; Engineering sense; Defending claims mathematically; Concern behaviour

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
How efficient knowledge / experience is used	We do not come with unattended problem, we must act fast, meaning, we use our experience and knowledge to solve the problem	During construction; Design stage	Monitoring and Control	Drawing reasonable solutions; Giving alternative solutions; Selecting/pursuing the right approach	Having discussion; Confirming; Considering relevant info;	Concern behaviour; Consciousness in assessing material
Informal knowledge / Intuition / imagining	Those skills come by experience, not stated in books….it is more to our experience, and experience teaches us a lot…	Design stage	Cognitive resources	Forming conjecture; Justifying reason; Self-consciousness	Considering relevant info;	Having mathematical views and sense-making; Engineering sense; Confidence
Intellectual curiosity	We have to know their needs, let say we build a road, how much depth is required, what is the purpose of building this road, or maybe we have to collect some data that is called traffic impact assessment to determine how many lanes are appropriate for the road.	Preliminary stage	Inquisitiveness	Seeking the best info; systematic	Considering relevant info; Seeking relevant info	Diligence in seeking info

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Justifying reasonably	As an engineer, he must be able to justify his design. If he says four pillars are sufficient for supporting the loading, and if he can justify it and prove it with code of practice, then, go ahead.	Design stage	Explanation	Concern behaviour; Selecting/pursuing the right approach	Having mathematical views and sense-making; Careful and prudent; Examining ideas Considering relevant info; Making conjectures	Dominating orientation; How efficient experience id used
Looking for patterns	Having good rapport and experience is priceless, they can be adapted in other projects, but for layout, definitely different as it cannot be reused, except for schools that following JKR standards	Design stage	Heuristics	Adapting into situation	Considering relevant info	How efficient knowledge / experience is used
Manipulating formula / input data/symbols/ equation	Sometimes we cannot get the answer from the software, so, we have to manipulate an equation to get another calculation	Design stage	Mathematical Practices	Having mathematical views and sense-making;	Transferring maths knowledge; Using standard equation	Maths consciousness
Mathematical proficiency	All stages involve mathematics, not so much at the input data, but, other than that, all involves mathematics	Design stage	Belief and Effect	Making/forming conjectures	Using formula; Manipulating data; Examining ideas; Clarify meaning; Comprehending	Maths consciousness

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Maths consciousness/ consciousness in assessing material	All stages involve mathematics, not so much at the input data, but, other than that, all involves mathematics	Design stage	Belief and Effect	Assessing statement; Self-consciousness	Giving alternative solution; Considering relevant info; Defending claims mathematically; Defending with good reasons	Selecting the right approach; Concern behaviour in making decision
Revising / reanalyse design	….when we produce our output, it will be commented by several parties, then, we have to revise accordingly	Design stage	Evaluation	Coming to grips with uncertainty	Counter checking; Simulate real life experience	Tolerant of divergent views
Selecting / Pursuing the right approach	If we want to get an info in structure, we use the right formula and it is being well followed, but, how we approach our clients, it depends on individual skills to accelerate the process	Preliminary stage; Design stage	Monitoring and Control	Tolerant of divergent views; (creativity) Concern behaviour; Adapting new approach	Justifying; Conforming ; Careful and prudent; Confidence; Considering relevant info; Applying theory/knowledge	Self-correcting; Drawing reasonable conclusion; How efficient experience is used
Self-consciousness	Sometimes we mistakenly typed it and then passed to draftsman, I have read a saying " there is no such thing as simple mistake for civil engineer' and until now I do remember it, so, to best possible,	Design stage	Self-reflection	Self-correcting; Concern behaviour	Checking thoroughly; Counter checking; Reviewing	Pursuing the right approach; Careful and prudent

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
	we have to minimize all the simple mistakes before producing the drawing					
Self-regulation	Some of the clients, even though we have not got approval of the submission, they insist to proceed. We can only agree with them with condition that if later, there are any comments from authority, we have to follow and if they agree, then only we proceed.	Preliminary stage; Design stage	Monitoring and Control	Concern behaviour; Tolerant of divergent views; Adapting to new approach	Cross-checking; Doing calculation; Justifying reasonably; Adjusting	Conforming; Pursuing the right approach
Simulate real life experience	…and for this, experience is helpful because we have to think of how will they execute it later, especially the contractor, if we do like this, how well can they do it?	Design stage	Heuristics	Forming conjectures; Coming to grips with uncertainty; Analytical reasoning skills	Checking thoroughly; Complying; Diligence in seeking info	Giving alternative ways; Tolerant of divergent views

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
Solving open-ended questions	When we investigated the soil, all was fine and we determined the place to do piling. But then, when they were doing the piling, the piling was broken, again and again, so, since we were facing the problem during that time, we had to make fast decision on what to do now, how to do…	During construction	Heuristics	Detecting failure; Selecting the right approach	Using evident to resolve problem; Making conjectures; Diligence in seeking info	Drawing reasonable conclusion; Defending with good reason Defending claims mathematically
Tolerant of divergent views	At the beginning stage, we have to confirm with client about the need statement, let say the owner wants to develop a bungalow, today he comes with this idea, so, we workout based on his idea, later, when we meet again, he has other different idea, so, this stage usually takes long time	All stages	Open mindedness	Concern behaviour	Justifying reasonably; Adjusting; Coming to grip with uncertainties	Self-regulation

Appendix E: Conditional Relationship Guide - continue

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
Understanding others' opinions	So far, I have never seen exactly the same approach been applied to different work, different clients have different ways and needs, so, we have to act accordingly, as long as it does not against our work ethic as an engineer.	All stages	Open mindedness	Concern behaviour; Self-correction	Having discussion; Flexibility in considering alternatives	Self-regulation; Decisions to be made along the way
Using evident to resolve problems	We had this misconception at the beginning, so, when it was wrong, obviously could see all the cracks. We panicked, at that time we had no professional engineer but only a supervisor, so, we sat down and discussed on what had happened and how to rectify it.	During construction	Analyticity	Detecting failure; Solving open ended problem	Having discussion; Making conjectures;	Decision to be made along the way
Using standard equation/formula/algorithm	Actually, indirectly, we use what we learnt, like calculus, and even though it is not directly applied, it is embedded in the formulae that we use for doing calculation.	Design stage	Cognitive resources	Applying knowledge	Manipulating formula; Manipulating data	Having mathematical views and sense-making; Mathematical proficiency

Appendix E: Conditional Relationship Guide - continue

Categories	**What (quotes)**	**Where (in…)**	**When (during…)**	**Why (because…)**	**How (by…)**	**Consequence**
Working backward	Our input determines our product, if we find some peculiar things at our product, we have to re-check its basic input data in computer, and this part requires manual knowledge	Design stage; During construction	Heuristics	Counter-checking input data; Revising	Examining output; Looking for patterns	Assessing output; Analytical reasoning