The Qualitative Report

Volume 21 | Number 2 Article 4

2-7-2016

Identifying Pertinent Elements of Critical Thinking and Mathematical Thinking Used in Civil Engineering Practice in Relation to Engineering Education

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Recommended APA Citation

Osman, S., Abu, M. S., Mohammad, S. b., & Mokhtar, M. b. (2016). Identifying Pertinent Elements of Critical Thinking and Mathematical Thinking Used in Civil Engineering Practice in Relation to Engineering Education. *The Qualitative Report*, *21*(2), 212-227. Retrieved from http://nsuworks.nova.edu/tqr/vol21/iss2/4

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Abstract

Engaging critical thinking and mathematical thinking in solving engineering problems is a way of approaching the engineering criteria of Engineering Accreditation Council, Board of Engineers Malaysia. Thus, it is timely and crucial to inculcate the critical thinking and mathematical thinking into the current engineering education. Unfortunately, information about these two modes of thinking in real-world engineering practice is found lacking in the literature. Therefore, this paper focuses on explaining an analytic process in identifying pertinent elements of critical thinking and mathematical thinking used in real-world civil engineering practice. The analytic process, namely open coding is a part of coding process in modified grounded theory analysis. Data consist of semi-structured interviews with eight practicing civil engineers from two different consultancy firms. A total of fifty three pertinent elements emerged during the analytic process. The selection of these pertinent elements was based on the predominant pattern and frequency of the informants and open codes. The pertinent elements were eventually integrated to develop a substantive theory. The substantive theory provides useful information for the engineering education.

Keywords

Critical Thinking, Engineering Education, Mathematical Thinking, Modified Grounded Theory

The Qualitative Report 2016 Volume 21, Number 2, Article 3, 212-227

Identifying Pertinent Elements of Critical Thinking and Mathematical Thinking Used in Civil Engineering Practice in Relation to Engineering Education

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Engaging critical thinking and mathematical thinking in solving engineering problems is a way of approaching the engineering criteria of Engineering Accreditation Council, Board of Engineers Malaysia. Thus, it is timely and crucial to inculcate the critical thinking and mathematical thinking into the current engineering education. Unfortunately, information about these two modes of thinking in real-world engineering practice is found lacking in the literature. Therefore, this paper focuses on explaining an analytic process in identifying pertinent elements of critical thinking and mathematical thinking used in real-world civil engineering practice. The analytic process, namely open coding is a part of coding process in modified grounded theory analysis. Data consist of semi-structured interviews with eight practicing civil engineers from two different consultancy firms. A total of fifty three pertinent elements emerged during the analytic process. The selection of these pertinent elements was based on the predominant pattern and frequency of the informants and open codes. The pertinent elements were eventually integrated to develop a substantive theory. The substantive theory provides useful information for the engineering education. *Keyword: Critical Thinking, Engineering Education, Mathematical Thinking, Modified Grounded Theory*

Ability to think independently is essential to succeed in today's globally connected and rapidly evolving engineering workplace (NAE, 2012). Therefore, it is timely and crucial to infuse real-world experiences into engineering education in addition to the existing excellent technical education. In view of that, program outcomes listed in the manual of Engineering Accreditation Council for the Board of Engineers of Malaysia (EAC/BEM, 2012) have emphasized on competency of engineering graduates in dealing with complex engineering problems, critical thinking skills development and evidence-based decision making in the curriculum. In addition, complex real-life problems often demand complex solutions, which can be obtained through higher level thinking processes (King, Goodson, & Rohani, 2008). A research conducted at a Malaysian private university shows that among the seven elements of soft skills to be implemented at all higher learning institutions in Malaysia, critical thinking and problem solving skills are the most important soft skills to be taught to engineering students (Idrus, Dahan, & Abdullah, 2010). However, comprehensive studies of critical thinking and an understanding of what critical thinking is, within the context of engineering are hardly to be obtained from the available literature (Douglas, 2006, 2012a, 2012b).

Similarly, critical thinking is generally recognized as an important skill and a primary goal of higher education. Yet, 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 et al., 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 is thought to support mathematical thinking and create the necessary bridge to link mathematics to problem solving in engineering (Rahman et al., 2013). Thus, an approach to support mathematical thinking and create the necessary bridge to link mathematics to problem solving in engineering is indispensable.

In addition, technical core of knowledge and breadth of coverage in mathematics, and the ability to apply the knowledge to solve engineering problems, are essential skills for civil engineers (BOK2 ASCE, 2008). This notion is 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 fundamental of engineering education for the 21st century engineers (Henderson & Broadbridge, 2007; Uysal, 2012). Furthermore, 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; MOE, 2012). However, there are no extensive descriptions delineating critical thinking elements for the engineering mathematics courses.

On top of that, findings from the previous studies have shown congruence between critical thinking and mathematical thinking in the real civil engineering workplace context (Radzi et al., 2011; Radzi et al., 2012). However, there is a lack of literature which indicates comprehensive overview, and research that rigorously investigates the interrelation and interaction between critical thinking and mathematical thinking in real-world engineering practice. In addition, there is no theory pertaining to the understanding of the process which may relate the mathematical thinking to the critical thinking. More importantly, understanding the interrelation and interaction among pertinent elements of these two modes of thinking is expected to contribute useful information to the engineering education. It seems helpful to lubricate and accelerate the process of understanding, applying and transferring mathematical knowledge into engineering education.

However, in order to infuse these critical thinking and mathematical thinking into engineering education, it is important to know what elements of these two modes of thinking are really used in the real engineering practice. Therefore, to identify pertinent elements of critical thinking and mathematical thinking used in real-world civil engineering practice becomes the main goal of this study. This paper focuses on explaining the analytic process for identifying the pertinent elements.

Role of the 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, I shared my experiences and background which have given a great impact to the way the study is articulated.

As a lecturer teaching mathematics and science to engineering students, I 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 I was 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, I 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 me that students need to be taught to think critically, particularly in mathematics learning. It is timely for having insight into the real-world practice about the interrelation and interaction between critical and mathematical thinking, to be incorporated into engineering education. The students need to be able to think critically to better understand and apply what they have learnt into other engineering subjects.

In addition, working in the quality control department at the pharmaceutical company as an analytical chemist for about eight years before joining the teaching profession, has exposed me in the real application of analytical, mathematical, and critical thinking. Looking back into the experience, I would like to share an interesting phenomenon which can be related to the teaching and learning in engineering education. For that, a specific real life scenario is quoted here. Calcium is supplement for better bone health. Milk is a rich source of calcium, yet, drinking a bucket of milk doesn't promise to supply the calcium we need. This is because, for calcium to be absorbed and used, it needs to have the right levels of other things, such as vitamin D. Taking calcium with vitamin D enhances the absorption rate of calcium. Now, by imagining calcium as mathematics, vitamin D as critical thinking and better bone health as good practicing engineers, it could be seen clearly the similarity of relevancy and significance of having critical thinking and mathematical thinking together in producing a good practicing engineer.

This perceived relationship may propose the existence of a close relevance between these two types of thinking in engineering workplace context. I become more positive with this perception when findings of the previous research have also shown an image of congruence between both types of thinking (Radzi et al., 2011; Radzi, Mohamad, Abu, & Phang, 2012).

For those reasons mentioned above, I believe that by having insight into the interrelation and interaction between critical thinking and mathematical thinking, the mathematics learning could be done in more effective way. It 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. It contributes to a body of knowledge useful empirical information that might help faculty and curriculum stakeholders to better prepare engineering students to use those skills to make meaningful contribution to the real-world engineering practice

Moreover, the perspectives from the lens of practicing engineers at the real-world practice could provide a better understanding among the students of how the skills being applied. It helps the engineering educators and students to have clear understanding about the relevance of the skills with engineering courses.

These prior perspectives can bias data acquisition and analysis. On the other hand, it improves my theoretical sensitivity in acquiring and analyzing data. While recognizing such methodological limitations due to the prior perspectives, I have taken steps to balance it. For that purpose, I 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.

As mentioned earlier, I worked as an analytical chemist before joining the teaching profession. Conducting chemical analysis in the laboratory required me to be focused and attentive when dealing with minute of chemical reagents. It required me to think critically and analytically in developing an analytical procedure, designing and testing phases of research and development products. I was responsible in documenting every analytical procedures and reports carefully. During the research and analysis phases, I had to accurately record all variables, such as type, amount and concentration of chemical reagents, compound components, chemical temperature and test duration. I 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 me to be a critical and analytical thinker, as well as nurturing good managerial skills. I, where appropriate, have adapted the experiences into this study, mainly during data acquisition and analysis. It increased my level of sensitivity in dealing with participants, handling and managing data acquisition and being reflective in writing memo and analyzing interview transcripts.

Methodology

This study adopts qualitative research method with modified grounded theory approach, based on Strauss and Corbin's version. Theoretical paradigms underlying the study are interpretive/symbolic interactionism and pragmatism. This research applies multiple paradigms to have more holistic and comprehensive understanding of the social phenomenon being studied. 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 participants (Denzin & Lincoln, 1994).

Strauss and Corbin (1994) mentioned that doing qualitative analysis is to make interpretations and must be based on multiple perspectives, in which 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). The inclusion of extant literature, especially in data analysis and theory generation during systematic comparison, was a consideration in selecting the research methodology (Strauss & Corbin, 1998). 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.

Data Acquisition

Data acquisition is oriented to grounded theory approach, which involves multiple stages of data generation and collection. In a grounded theory study, the selection of participant is intentional and focused on narrowing the theoretical sampling to allow Ito examine only participants that can contribute to the generation of a theory (Creswell, 2014). Participants of this study comprised of eight experts from two civil engineering consultancy firms in southern region of West Malaysia. The selected engineers have a minimum of five years' experience in this field of engineering design. 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.

Conducting interviews and writing memos were used for data generation in this study. Many grounded theorists rely heavily on interviewing as a way to capture best the firsthand experiences of participants (Creswell, 2014). Data were generated from semi-structured interviews with eight participants. Time duration for each interview was about two hours. The researcher audio-recorded and transcribed the interviews. Table 1 shows summary demographic information regarding the participants from both consultancy firms with alternate names for anonymity and the duration of the interviews.

Table 1: Summary of Interview Participants

Site	Interview Participants	Gender	Designation	Experience in Engineering Design (Years)	Duration of Interview (Minutes)
Firm A	Engineer 1	Male	Professional Engineer, Company Director	20	85
Firm A	Engineer 2	Female	Engineer	6	82
Firm A	Engineer 3	Female	Engineer	5	82
Firm A	Engineer 4	Female	Senior Engineer	15	150
Firm A	Engineer 5	Male	Senior Engineer	15	150
Firm B	Engineer 6	Male	Professional Engineer	15	63
Firm A	Engineer 7	Male	Professional Engineer, Company Director	20	107
Firm B	Engineer 8	Female	Engineer	8	85

This study used two types of sampling methods, namely purposive sampling and theoretical sampling. At the beginning of the study, as no theoretical concepts and categories was available to be referred to, initial or purposive sampling method was applied (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, participants 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 study, data were collected and generated from literature review and findings from the preliminary and pilot studies. Those data gave information for selecting participants with purposive sampling during the main study. As data acquisition and analysis are run concurrently, each interview leads to further subsequent interviews as new information and themes emerge from previous interview data analysis (Johnson & Christensen, 2000).

The emergent categories derived from data determined the orientation of the following interview. Therefore, samples of potential participants as mentioned earlier, for interview and observation, were purposely chosen in view of gathering data related to the properties and dimensions of the targeted categories (Strauss & Corbin, 1998). It was known as doing theoretical sampling. The theoretical sampling was 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). Sampling choices were dictated by the evolving categories derived from data, of the emerging theory (Corbin & Strauss, 2008; Khiat, 2010). In doing the theoretical sampling, strategic decision about the most information-rich source of data and questions used to collect data was determined (Birks & Mills, 2011). It was to ensure that the newly developed substantive theory is theoretically complete. This function is an important feature of theoretical sampling (Elliott & Lazenbatt, 2005).

The categories generated from data determined the appropriate and relevant interview questions and interviewees. It repeated until reach the saturation level in which no more new theme and concept are emerged from the new data acquisition. This iterative process continues until properties and dimensions of categories under development are saturated with information needed. Figure 1 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 was actively carried out along the sampling and data analysis process 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).

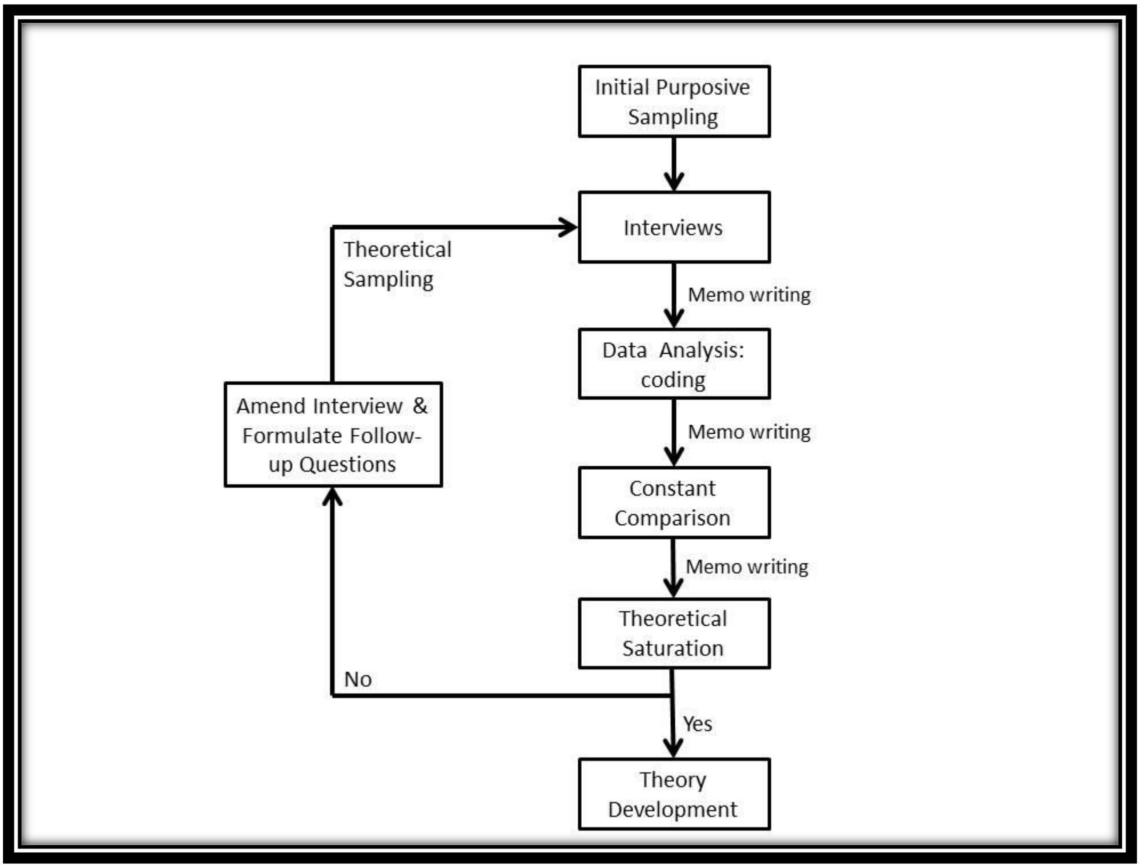

Figure 1: Iterative process of sampling in grounded theory analysis

Data Analysis

According to the typical procedure of grounded theory, data acquisition and data analysis are interrelated and carried out simultaneously. This is to allow the occurrence of two analytic procedures pertaining to the constant comparative method of analysis and the asking of questions (Strauss & Corbin, 1990, 1998). In the modified grounded theory analysis, three basic analytic process involved, namely open coding, axial coding and selective coding (Corbin & Strauss, 1990; Strauss & Corbin, 1990, 1998). This study needs to identify pertinent elements of critical thinking and mathematical thinking through open coding before explaining the interrelation and interaction among the elements through axial and selective coding.

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 Ito the complete range of data to gain greater understanding of potential meanings contained within the words used by participants (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) .

Therefore, this paper explains in detail the analytic process of open coding for identifying pertinent elements used in real practice of civil engineering. I analyzed data and did the coding process manually. 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. Data were analyzed using constant comparative method which relying much on the theoretical sensitivity.

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 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). 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.

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 Ito 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 coding. Each interview transcripts was compared with previous data and not considered on its own, enabling me to treat data from all the transcripts as a whole rather than fragmenting it. As I play an active role in this constant comparison process, it is important for me to have theoretical sensitivity, which is fostered in the comparison phase (Johnson & Christensen, 2000; Strauss & Corbin, 1998).

Theoretical Sensitivity. Theoretical sensitivity is a characteristic of the researcher, involves a mixture of analytic thinking ability, curiosity and creativity (Johnson and 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 participants 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.

Furthermore, I do not have to enter the research field with blank mind or tabula rasa, as it often assumed (Glaser & Strauss, 1967). Having predetermined ideas could enhance theoretical sensitivity by providing concepts and relationships that are checked out against actual data. It enables me to see relevant data and abstract significant categories from the scrutinized data. Constant comparative method for analyzing data in grounded theory treats literature as “data” and repetitively compare it with emerging categories which then are integrated in the theory. The properties and dimensions brought out from the comparison method were used to examine the data (Strauss & Corbin, 1998). Additionally, by doing data collection and analysis concurrently, makes Ito 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.

Analytic Process of Identifying Pertinent Elements. Analyzing interview transcripts for open coding was not an easy task. I had to make my thinking flexible in two different forms. The first round of analysis required me to immerse myself into the participants’ world to understand about design process. I read the transcripts several times and then, conceptualized the content that related to the design process into appropriate themes. For the second round, I read again the transcripts thoroughly to capture elements of critical thinking and mathematical thinking used in the real-world practice.

For the purpose of identifying the pertinent elements, I outlined six steps of data analysis strategies. 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 was initiated on the first transcript as soon as it was transcribed closely after the first interview. Each transcript was coded inductively. 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 analyzed transcripts. 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.

Then, the inductive codes obtained were classified as critical thinking or mathematical thinking, through the lenses of Facione for critical thinking and of Schoenfeld for mathematical thinking. 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 thinking. Thus, the third step was to determine the total repetition number of open codes for the core skills of critical thinking.

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. 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.

This method, covering steps from the first until the fifth was applied as a whole to each interview transcripts. 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 participants. 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, I 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 deployed. The Microsoft Excel file listed the informants and frequency for open codes of core skills of critical thinking emerged from the previous steps of data analysis. The same step was applied for tabulation of the open codes for the dispositions of critical thinking and also for the cognitive aspects of mathematical thinking.

The pertinent elements were identified according to the predominant pattern and frequency in the listing. As a basis of the identifying process, I set minimum criteria for the selection. For the predominant pattern, number of participants 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 were 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.

Results

A total of fifty-three selected categories emerged from about two hundreds open codes during the open coding process. These selected major categories were the pertinent elements of critical thinking and mathematical thinking mainly used in real-world civil engineering practice. The selection of these pertinent elements was based on the predominant pattern and frequency of the informants and open codes. List of the pertinent elements were tabulated as in Table 2.

The pertinent elements were then subjected to the next analytic process. During axial coding, the interrelation among these pertinent elements was established. From that, the interaction among the pertinent elements was then explained during selective coding through the process theory story line. Eventually, a substantive theory pertaining to critical thinking and mathematical thinking used in real-world engineering practice was developed.

Table 2: The Pertinent Elements of Critical Thinking and Mathematical Thinking

Adapting new/different approach / situation / experience	*Counter checking*	*Intellectual curiosity*
Amending	*Decision to be made along the way*	*Justifying reasonably*
Analytical reasoning skills	*Defending claims mathematically*	*Looking for patterns*
Anticipating the results	*Defending with good reasons*	*Manipulating formula / input data/symbols/ equation*
Applying / transferring maths knowledge / theory	*Detecting failure*	*Mathematical proficiency*
Assessing credibility of output / info	*Diligence in seeking info*	*Maths consciousness/ consciousness in assessing material*
Careful and prudent	*Dominating orientation*	*Revising / Reanalyse design*
Checking thoroughly	*Drawing reasonable conclusion*	*Selecting / Pursuing the right approach*
Clarifying meaning	*Engineering sense*	*Self-consciousness*
Coming to grip with uncertainties	*Examining Ideas / output*	*Self-regulation*
Complying	*Flexibility in considering alternatives*	*Simulate real life experience*
Comprehending	*Forming conjectures / assumption*	*Solving open-ended questions*
Concern behaviour in making decision	*Gathering info/data/relevant info*	*Tolerant of divergent views*
Confidence in reasoning	*Giving alternative ways / solutions*	*Understanding others' opinions*
Confirming	*Having discussion*	*Using evident to solve problems*
Conforming	*Having mathematical views and sense-making*	*Using standard equation/formula/algorithm*
Considering relevant info	*How efficient knowledge / experience is used*	*Working backward*
Correcting / Self correction	*Informal knowledge / Intuition / imagining*	

Discussion

The goal of this study was to develop a substantive theory pertaining to critical thinking and mathematical thinking 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.

This paper focuses on explaining the process for identifying the pertinent elements of critical thinking and mathematical thinking during open coding. Open coding is one of the three stages of analytic process in grounded theory analysis. The identified pertinent elements provide useful information to engineering education regarding the skills used in real-world engineering practice. It helps engineering educators to identify and incorporate the pertinent skills from real engineering experience 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, this study provides clear understanding to the engineering educators about the relevance of critical thinking and mathematical thinking to engineering courses.

Implication of the Substantive Theory for Engineering Education

As mentioned earlier, the pertinent elements were eventually integrated in developing a substantive theory. The substantive theory provides useful information on the relation between critical thinking and mathematical thinking for engineering education. The information 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, I intend to promote the substantive theory to the civil engineering curriculum, focusing mainly on integration of the theory into the mathematics instruction for civil engineering students with some considerations as follows.

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 : 1) An ability to apply knowledge of mathematics, science, engineering fundamentals and an engineering specialisation to the solution of complex engineering problems; 2) 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 3) 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).

Therefore, 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 2 to illustrate the role of the theory in civil engineering instructions. The substantive theory (ST) is infused into the instructions of engineering mathematics (EM) and other civil engineering (CE) subjects.

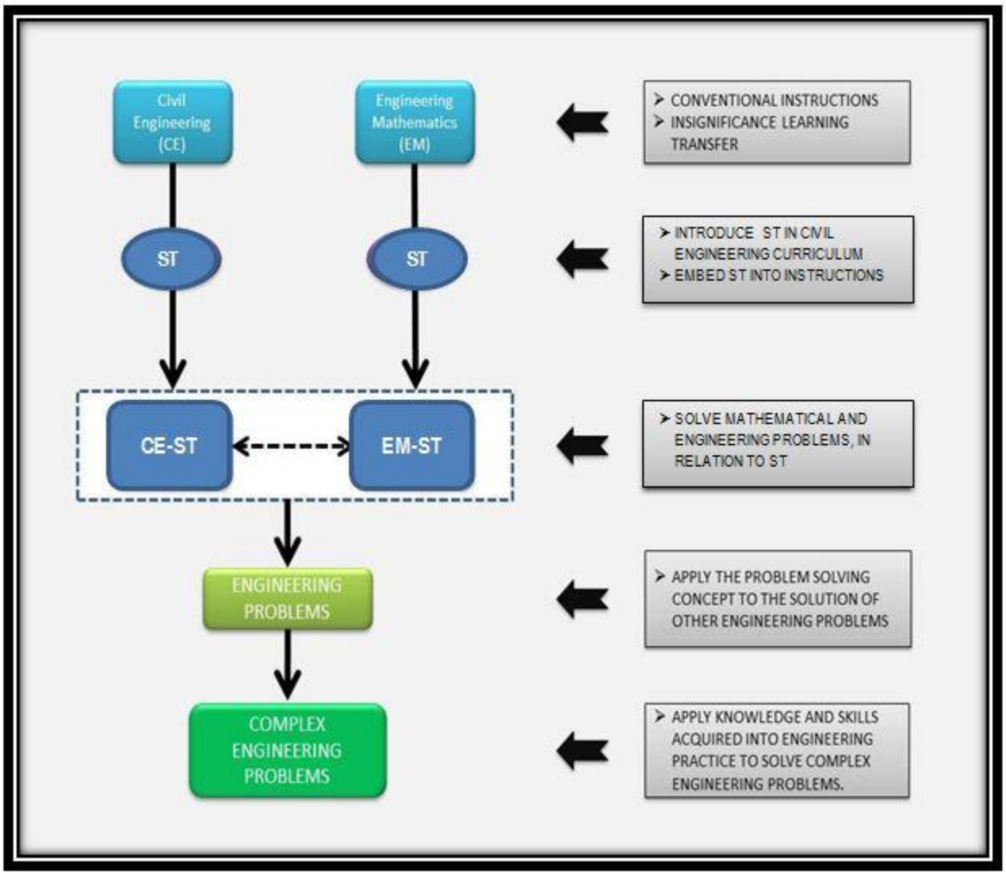

Figure 2: Schematic Diagram Showing the Role of Substantive Theory in Civil Engineering Instructions

Conventional instructions are too specific-domain and thus, might have caused an insignificance learning transfer. Embedding ST into the instructions allows its integration across the curriculum and for that, the prescribed content materials in conventional instructions need to be restructured. Students of civil engineering programme that would be treated with these ST-embedded instructions are expected to be able: 1) to solve mathematical and engineering problems in relation to ST; 2) to apply the problem solving concept to the solution of other engineering problems; and 3) to apply knowledge and skills acquired into engineering practice to solve complex engineering problems.

Additionally, by recognizing the role of ST in engineering design process may help engineering educators to better guide students how to engage in the ST and transfer the knowledge material they have learned across the engineering courses and 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.

Introducing ST in civil engineering curriculum shall provide students with ample opportunities to understand and acquire basic principles and skills of the discipline. 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.

The propose recommendations for integrating ST 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 ST able to spark an initial trigger for a new turn of emphases on instructional approaches.

As mentioned above, the pertinent elements were eventually integrated in developing a substantive theory. The emergent substantive theory is related to the decision making process in solving problems in engineering design. An explicit description of that process theory 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).

Limitation of the Study

Important considerations in this study were related to the scope of engineering investigated and the background and professionalism of the research participants. The scope of engineering investigated was the real-world practice of civil engineering, focusing on the engineering design process. A total of eight practicing engineers from two civil engineering consultancy firms were interviewed as participants for this research. The engineers selected to participate in this study have had at least five years' experience in the field of civil engineering design. The data collected from the interviews were limited to the participants' 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 participants 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 participants 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.

Conclusion

This paper discussed in detail the process of identifying pertinent elements of critical thinking and mathematical thinking used in real-world engineering practice. This study contributes to engineering education body of knowledge by providing useful empirical information for engineering curriculum, educators and students. The 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 real-world engineering practice is still found wanting in relation to its importance in engineering education.

Therefore, this study, to my 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.

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Article Citation

Osman, S., Abu, M. S., Mohammad, S., & Mokhtar, M. (2016). Identifying pertinent elements of critical thinking and mathematical thinking used in civil engineering practice in relation to engineering education. *The Qualitative Report*, *21*(2), 212-227. Retrieved from http://nsuworks.nova.edu/tqr/vol21/iss2/4