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INTEGRATING PERTINENT ELEMENTS OF CRITICAL THINKING AND MATHEMATICAL THINKING USED BY PRACTICING CIVIL ENGINEERS IN GROUNDED THEORY ANALYSIS

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ABSTRACT

This paper explains process of integrating the pertinent elements of critical thinking and mathematical thinking using Straussian grounded theory methodology. The process of integrating the pertinent elements occurs during selective coding process in the grounded theory analysis. Findings from open coding and axial coding process are the main source of information for development of the selective coding. The selective coding process employs the reflective coding matrix to develop and contextualize the core category. The refined core category depicts the process theory of justifying decision reasonably in dominating orientation. A conditional matrix is then developed as a coding device to visualize the process theory. The study contributes useful information to engineering education instructions, which is aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council.

Indexing terms/Keywords

Critical thinking, mathematical thinking, Straussian grounded theory, qualitative research, research methodology, engineering education

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INTRODUCTION

Critical thinking is generally 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 available literature (Douglas, 2006, 2012a, 2012b). In the same way, the current scenario to facilitate civil engineering students' learning of engineering mathematics seems to be inadequate in enhancing students' ability to apply the mathematical knowledge and skills analytically and critically. 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, and Firouzian, 2013; Rebello and Cui, 2008; Townend, 2001; Yusof and Rahman, 2004). The transfer of knowledge remains problematic and needs to find ways for better integrating mathematics into engineering education (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. Nevertheless, findings from the previous study have shown congruence between critical thinking and mathematical thinking (Radzi, Abu, Mohammad, and Abdullah, 2011; Radzi, Mohamad, Abu, and Phang, 2012). It indicates an existence of a close relationship between these two thinking in the real civil engineering workplace context. Accordingly, this study is conducted to generate a substantive theory pertaining to critical thinking and mathematical thinking, which is currently still lacking in relation to the civil engineering practices. Insight into the interaction among pertinent elements of these two thinking is anticipated to lubricate and accelerate the process of understanding, applying and transferring mathematical knowledge into engineering education.

This study employs the Straussian grounded theory methodology (Strauss and Corbin, 1990, 1998). The inclusion of existing experiences and knowledge, especially in data analysis and theory generation during systematic comparison, was a consideration in selecting the research methodology (Strauss and Corbin, 1998). Moreover, researchers often build new knowledge on existing knowledge for cumulative theory development (Goldkuhl and Cronholm, 2010). For that, ignoring existing knowledge tends to be a waste when duplicating a basic method that has already previously been created or optimized by others. Additionally, in the context of this study, the existing knowledge is also used for minding the scattering amplitude of the collected data to be reasonably confined and manageable. Therefore, to be within a reasonable confinement, this study refers to the perspectives of Facione for critical thinking (Facione, Facione, and Giancarlo, 2000; Facione, 1990, 2007, 2013) and Schoenfeld for mathematical thinking (Schoenfeld, 1985, 1992).

Strauss and Corbin (1990, 1998) asserted that grounded theory is an action/interactional method of theory building and allows analytic tools or techniques to be used during data analysis process. In line with their assertion, this study uses research tools as data-oriented conceptual clarification, namely the conditional relationship guide and the reflective coding matrix as prescribed by Scott (Scott and Howell, 2008; Scott, 2004) . These tools are used to support grounded theory analysis and interpretation by linking categories more clearly to the data. This paper provides detailed explanation of the usage of reflective coding matrix in the selective coding process.

METHODOLOGY

Research Approach and Philosophy

This study employs qualitative research using Straussian grounded theory approach. 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.

Research Informants

Informants of this study comprised of eight experts from two civil engineering consultancy firms in southern region of West Malaysia. These firms are chosen because all the data needed for this study can be acquired and their nature of work at these places is coherent with the requirements of the intended research. The informants are practicing and professional civil engineers, who are experienced in civil engineering design for at least five years.

Data Acquisition

Data acquisition is oriented to grounded theory approach, which involves multiple stages of data generation and collection. Data were generated from semi-structured interviews with eight informants. The duration for each interview was about two hours. The interviews were audio-recorded and transcribed by the researcher. Additionally, data were collected from pertinent literatures and documents. 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 incident in the data (Strauss and Corbin, 1998).

This study used two types of sampling methods, namely purposive sampling and theoretical sampling. 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, 2014). Data were collected and generated from the literature review and findings from preliminary and pilot studies. Those data gave information for selecting participants in purposive sampling. In this study data acquisition and analysis ran concurrently whereby each interview leads to subsequent interviews as new information and themes emerged from the previous interview data analysis (Johnson and Christensen, 2000). Theoretical sampling is based on the emergent categories derived from data. It determines strategic decision about what or who will provide the most information-rich source of data to meet analytical needs. Thus, the concepts and categories generated from the data in this study were used to determine the interview protocol. The interview sessions were conducted until saturation level was achieved whereby no new theme and concept emerged from collected data. In addition, memos were written since memos or diagrams were important during this process in order to relate possible sources to sample, to act as repositories of thought in creating an important audit trail of the decision-making process for later use (Birks and Mills, 2011; Corbin and Strauss, 2008).

Ethical Consideration

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.

Trustworthiness and Quality of Research

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

- Are concepts generated?
- Are concepts systematically related?
- Are there many conceptual linkages and are the categories well developed? Do categories have conceptual density?
- Is variation within the phenomena built into the theory?
- Are the conditions under which variation can be found built into the study and explained?
- Has process been taken into account?
- Do the theoretical findings seems significant and to what extent?
- 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. 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, conformability, dependability/auditability, credibility and transferability for interpretive world view.

Grounded Theory 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 and Corbin, 1990, 1998). In this study, three basic analytic process involved, namely open coding, axial coding and selective coding (Corbin and Strauss, 1990; Strauss and Corbin, 1990, 1998). Data were analyzed solely by the researcher and coding process was done manually. However, the analysis and emergent codes and categories were reviewed and verified by the experts in the related fields to ensure trustworthiness. Microsoft Words 2010 and Microsoft Excel 2010 were used to assist the organization and management of data.

Open and Axial Coding

Open coding is the first stage of data analysis, begins after some initial data have been collected, which involves labelling and categorizing the phenomenon as indicated by the data using in vitro or in vivo codes (Birks and Mills, 2011). The researcher transcribed all interviews and the transcripts of the interview are the main data source in this analysis. The selection of pertinent elements of critical thinking and mathematical thinking was executed during the open coding process based on the emergent predominant pattern and frequency of the informants and open codes. Pertinent elements were identified among the emergent codes, through the lenses of Facione's critical thinking skills and dispositions and five aspects of cognition of Schoenfeld's mathematical thinking. As a basis of the identifying process, the researcher 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.

A total of fifty three selected categories emerged from about two hundreds open codes during the open coding process. These selected categories are the pertinent elements of critical thinking and mathematical thinking, which are mainly used in the real-world civil engineering practice. Subsequently, the interrelation among the pertinent elements was empirically developed during the axial coding process, using the conditional relationship guide. Axial coding is an intermediate stage of coding process. Those deconstructed data during open coding were gathered back together in new form by creating associations between categories, in which, open coding and axial coding go hand in hand (Corbin and Strauss, 2008; Strauss and 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 and Mills, 2011). An example of conditional relationship guide is shown below in Table 1.

Table 1: Example of Conditional Relationship Guide

Categories	What (quotes)	Where (in…)	When (during…)	Why (because…)	How (by…)	Consequence
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. Thus, mathematical thinking is important in designing.	Design stage; During construction	Self-reflection	Concern behaviour; Conforming	Working backward; Looking for pattern; Checking thoroughly	Correcting; Selecting the right approach

Interrelation between the pertinent elements was identified by answering the questions, what, where, when, why, how and with what consequences. Employing 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, 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. After excluding the set-aside pertinent elements, there were left twenty four major consequences, as shown in Table 2. These major consequences play an important role in constructing the reflective coding matrix during the selective coding process.

Selective Coding

Selective coding is the third stage of coding process for integrating and refining categories. It is initiated by deciding on a core category, and systematically relating the core category to other categories, and validating those relationships, as well as filling in categories that need further refinement and development (Strauss and Corbin, 1990, 1998). Whereby the core category is the main theme of the research (Strauss and Corbin, 1998) and the central phenomenon around which all the other categories are integrated. From the interrelation among the pertinent elements established by the conditional relationship guide in axial coding process, the consequences are identified as the key categories about which all other categories are focused. There were twenty four major consequences appeared as shown in Table 2. These major consequences become the main contributor to the development of core category. There are several possible ways in developing the core category. The researcher used the reflective coding matrix to determine the core category, which can be described in terms of its properties, processes, dimensions, contexts, and the modes with which its consequences are understood. Once the core category was determined, all other categories become sub-categories.

Table 2: Major Consequences

Pertinent Elements as Major Consequences
Careful and prudent
Complying
Concern behaviour in making decision
Confidence in reasoning

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-correction
Self-regulation
Tolerant of divergent views

The researcher started the process of developing 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 was 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 positioning categories during axial coding process is like fitting 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, the process of identifying the reflective coding matrix descriptors is like completing a jigsaw puzzle, trying a piece at a time until it all fits and makes sense (Scott, 2004). Details of the process of developing the matrix are discussed below.

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, forming conjectures, drawing reasonable conclusion, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach. Subsequently, for the contexts, the s cope was focused on the purpose of this study to understand the interaction among pertinent elements of critical thinking and mathematical thinking. Therefore, the researcher chose Facione's core skills of critical thinking and Schoenfeld's five aspects of cognition of mathematical thinking in determining the contexts, according to the related major consequence categories in the processes.

Next stage is to identify the dimensions. 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 guide, became dimensions for each particular process in the matrix. There is also possibility the same categories are identified as dimensions of different processes. Nevertheless, they are refined later after the core category was identified.

Another descriptor on the matrix to be taken into account is the modes for understanding the consequences. This descriptor is also known as process outcome. As mentioned above, pertinent elements 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. Next stage is to make an educated guest about the core category. In the explanation below, all codes are italicized. 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.

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 designing 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 designing 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 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. So, 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 were determined at the earlier stage of developing the matrix, they are now abstracted to a higher level in naming the properties. At this stage of analysis, once the matrix is fully developed, see Table 2, 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.

Table 2: Reflective Coding Matrix

Core Category	**Justifying decision reasonably in dominating orientation**					
Processes (action/interaction)	Complying requirements	Forming conjectures / assumption	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 ▪ Diligence 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

The process theory is then visualized through a conditional matrix as shown in Figure 1. The conditional matrix is a coding device to help the researcher to keep in mind several analytic points such as the processes and the consequences depicted in the reflective coding matrix (Strauss and Corbin, 1998). 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. The inner ring represents the process outcome, which is the mode for understanding the consequence of each process involved in justifying a decision. The outer ring 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*. The process, *complying requirements,* with its process outcome, is placed at the most outer ring of the conditional matrix to denote a fundamental to all other processes. The thick arrows at the most outer ring that showing continuous direction, indicate the process is continuously taken into account throughout the stages of designing. The thin arrows placed at the outer ring towards the center of the conditional matrix, segregating the five processes, are showing particular involvement of each process towards justifying a decision reasonably. This conditional matrix helps to further understanding of the interaction among the pertinent elements of critical thinking and mathematical thinking, as experienced by the practicing civil engineers.

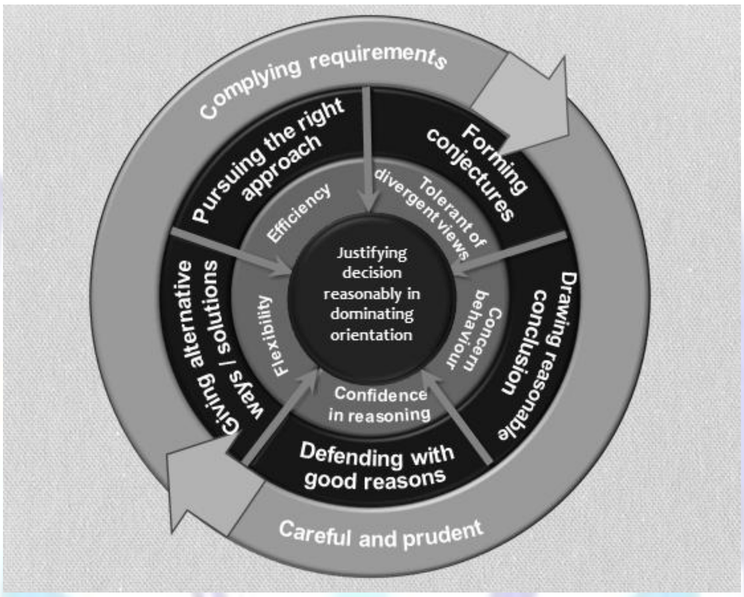

Figure 1: Conditional Matrix Representing the Processes of Justifying Decision Reasonably

DISCUSSION

This study shows that *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 consequences. It was through the iterative process of developing the reflective coding matrix that *making decision* was refined and eventually fully described as *Justifying Decision Reasonably in Dominating Orientation*. The interaction among the pertinent elements in relation to the refined core category was depicted through the reflective coding matrix used in the selective coding process. In brief, the theory reflects what the design engineer thinks when making design decisions.

This study provides empirical information which can be incorporated in a learning instruction. In view of that, there are four areas that instruction should include to maximize learning, as described by (Bransford, Brown, and Cocking, 1999), in the How People Learn (HPL) model. According to this paradigm, instruction should be student-centered; knowledge-centered; assessment-centered; and community-centered (Svinicki, 2010). This study seems to provide some useful information to the engineering education instructions 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 practices is a workable pair complementing each other, in relation to the theories of student-centered learning. A number of studies have been conducted on critical thinking (see, for example, (Aizikovitsh and Amit, 2009, 2011; Douglas, 2006, 2012a; Jacquez, Gude, Hanson, Auzenne, and Williamson, 2007; Luan and Jiang, 2014; Marcut, 2005; Norris, 2013) and mathematical thinking (see, for example, (Burton, 1984; Cardella and Atman, 2007; Cardella, 2006; Kashefi, Ismail, Yusof, and Rahman, 2012a, 2012b; Rahman et al., 2013; Yusof and Rahman, 2004), in relation to mathematics and engineering. Unfortunately, none has been found doing study on both critical thinking and mathematical thinking, mainly on the use of both thinking in the real-world engineering practice. Therefore, this study highlights that having insight into the 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 is focusing on helping educators develop a profound understanding of the content and processes of the discipline. A study on faculty members, who have improved significantly in their teaching 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 and 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 the students need to develop, include the skills in the course syllabus and communicate their importance to the students (Woods, Felder, Rugarcia, and Stice, 2000). This is to ensure the students understand the relevance of the skills to their professional success, through the discussion about the skills at the same level of seriousness and enthusiasm when the technical content of the course is presented. Therefore, having insight into the interaction among pertinent elements of critical thinking and mathematical thinking is expected to give clear understanding about the relation between critical thinking and mathematical thinking, and engineering courses, which is currently still lacking in relations to the civil engineering practices.

CONCLUSION

This study reveals that integrating the pertinent elements of critical thinking and mathematical thinking in grounded theory analysis is to understand the interaction among the pertinent elements of critical thinking and mathematical emerged during the open coding process. The interaction among the pertinent elements is explained through the process of identifying the core category and the formation of the substantive process theory from the refined core category. The process theory named justifying decision reasonably in dominating orientation comprises six processes: complying requirements, forming conjectures, drawing reasonable conclusion, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach.

The process theory is based on civil engineers' experiences in designing projects. This study contributes useful information to engineering education instruction, which is aligned with the expectations of engineering program outcomes set by the Engineering Accreditation Council. In the same way, in regard to the engineering design process in the real-world engineering practice, critical thinking and mathematical thinking can be incorporated into the learning instruction and actively taught to the civil engineering students.

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