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Math-Related Critical Thinking Theory in Civil Engineering Design

Sharifah Osman[1*], Shahrin Mohammad[2], Mohd Salleh Abu[1], Mahani Mokhtar[1], Muhammad Abd Hadi Bunyamin[1], Abdul Halim Abdullah[1] , Hanifah Jambari[1] and Jamilah Ahmad[1]

[1]*Faculty of Education, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*
[2]*Faculty of Civil Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor, Malaysia*

ABSTRACT

Design is the fundamental soul to all branches of engineering. It is a prime context for understanding how civil engineers use critical thinking and mathematical thinking in engineering problem-solving. However, information about the interrelation between these two types of thinking in real-world engineering practice is found lacking in the literature. This paper presents the first-hand experience of developing a substantive theory which relates both critical thinking and mathematical thinking used by practicing engineers in the civil engineering design process. The qualitative research using modified grounded theory method was employed in this study. Data were generated from semi-structured interviews with practicing engineers from two engineering consultancy firms. Six essential processes of justifying decisions reasonably in engineering design process were identified, namely complying requirements, forming conjectures, drawing reasonable conclusions, defending claims with good reasons, giving alternative ways and selecting and pursuing the right approach. Findings of this study may advise prospective civil engineers of the applicability and indispensability of critical thinking and mathematical thinking in making and justifying decisions during the engineering design process. The study also contributes useful information to engineering education on fulfilling the expectations of engineering program outcomes set by the Engineering Accreditation Council.

Keywords: Civil engineering, critical thinking, decision making, design process, mathematical thinking, problem-solving

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E-mail addresses:
sharifah.o@utm.my (Sharifah Osman)
shahrin@utm.my (Shahrin Mohammad)
salleh@utm.my (Mohd Salleh Abu)
p-mahani@utm.my (Mahani Mokhtar)
mabhadi@utm.my (Muhammad Abd Hadi Bunyamin)
p-halim@utm.my (Abdul Halim Abdullah)
hanifah-j@utm.my (Hanifah Jambari)
jamilah_a@utm.my (Jamilah Ahmad)
* Corresponding author

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INTRODUCTION

Engineering is a people-oriented profession. Engineers are hired for their abilities and expertise to solve workplace problems. The essential learning outcomes for any engineering program are to equip engineers with abilities to apply, identify, design, and solve engineering problems (EAC-BEM, 2012; Engineering Accreditation Commission [ABET], 2014). Engineering fields are characterized into four main branches: chemical engineering, civil engineering, electrical engineering, and mechanical engineering. This study 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 to 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 a 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 closely 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 (Bureau of Labor Statistics, U.S. Department of Labor, 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 the civil engineering design process. Design is the fundamental soul to all branches of engineering. It is a decision-making process where the content knowledge of mathematics, science and engineering courses is integrated and applied (Cardella & Atman, 2007) to convert resources optimally to meet desired needs. Design is a form of problem-solving that is open-ended and complex (Jonassen, 2000). Therefore, design is a process reliant and the solution is subjected to unforeseen complications and changes as it develops (Khandani, 2005). 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.

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. 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 an 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, 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. Therefore, this study aims to have insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking, as perceived by civil engineers during engineering design process.

METHOD

This study used a systematic set of procedures of the modified grounded theory method to analyse data for identifying themes within engineering experiences shared by practicing engineers. Data were generated from semi-structured interviews with practicing engineers from civil engineering consultancy firms. The informants were chosen from civil engineering consultancy firms, focusing on the civil engineering design process. The selected engineers must 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 a wider scope of past and present design experience.

As a methodological framework, this study employed qualitative research using inductive, deductive and abductive approaches in Strauss and Corbin's version of a modified grounded theory method. In this analytic induction approach, data from interviews built the basis for further description and interpretation. In the grounded theory method, data acquisition and data analysis are interrelated and carried out simultaneously. Findings from the interview data determine the orientation of the subsequent interviews in theoretical sampling. This iterative process is continuing until it reaches the theoretical saturation. Multiple stages of analytic process involved, namely open coding, axial coding and selective coding (Corbin & Strauss, 1990; Osman et al., 2015c; Strauss & Corbin, 1990, 1998). Two analytic tools were used in the analysis namely Conditional Relationship Guide (CRG) and Reflective Coding Matrix (RCM) (Scott & Howell, 2008).

The Straussian grounded theory approach is chosen due to its more inclusive attitude to the extant literature and systematic approach to data analysis that involves inductive, deductive and abductive approaches. The inductive approach is a data-driven strategy which develops themes emergently based on patterns in the data (Daly et al., 2013). Codes/categories/themes are emergently developed during open coding process of raw data. The deductive approach 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, this strategy was applied during data analysis process and throughout the constant comparative method that used 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. Abductive approach is an analytic induction for generating new ideas from a combination of the fundamental approaches of inductive and deductive (Suddaby, 2006). It allows researchers 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 the constant comparative method. To conclude, this study adopts the abductive approach as an analytic induction for generating new ideas from a combination of the fundamental inductive and deductive approaches.

The process of selecting pertinent elements of critical thinking and mathematical thinking was carried out at the initial stage of the analysis. Pertinent elements were identified from the emergent codes during open coding (Osman et al., 2016), from the lens of Facione (Facione, 1990, 2007, 2013; Facione et al., 2000) for the core skills and dispositions of critical thinking and Schoenfeld (1985, 1992) for the five aspects of cognition of mathematical thinking. Subsequently, the interrelation among the pertinent elements was empirically established through axial coding, using the CRG (Osman et al., 2015b). Ultimately, all the pertinent elements were integrated and systematically related to the core category during the selective coding process. The interaction among the pertinent elements in relation to the core category was depicted through the RCM used in the selective coding process (Osman et al., 2015a). However, the emergent categories were reviewed and verified by the experts in those particular fields to ensure trustworthiness. Microsoft Word 2010 and Microsoft Excel 2010 were used to assist the organization and management of data.

The fully developed RCM shows the refined Core Category, *justifying decisions reasonably in dominating orientation,* with the six related processes: *complying requirements, forming conjectures, drawing reasonable conclusions, defending claims with good reason, giving alternative ways and selecting and pursuing the right approach*. Through the CRG and RCM, the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking in developing the emerging theory are established.

RESULTS AND DISCUSSION

The emerging theory of Math-related Critical Thinking comprises pertinent elements of critical thinking and mathematical thinking used by civil engineers in real-world engineering design practice. 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 civil engineering design practice. Apparently, in order to solve engineering problems, engineers need to make decisions and justify the decisions reasonably. From the CRG and RCM, the explanation below explicitly describes the story line of the process theory, referring to the six essential processes: complying requirements, forming conjectures, drawing reasonable conclusions, defending claims with good reasons, giving alternative ways and selecting and pursuing the right approach. This explanation answers the aim of this study that to have insight into the interrelation and interaction among pertinent elements of critical thinking and mathematical thinking, as perceived by civil engineers during the engineering design process. The explanation provides verbatim quotations from informants as support, and all quotations and codes are italicized.

Complying Requirements

Along the process, at all stages of design, 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*.

Likewise, *confirming* a status prior to 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."* (Engineer 7)

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.

> *"Safety factor cannot be ignored, and the cost as well, so, by having an engineer can diversify the design with minimal cost but safety is always prioritized. To me, this is the role of an engineer....again, the safety factor is our priority."*
> (Engineer 7)

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 that, if realized that we have over designed it, we can reduce the size from the result obtained using software."* (Engineer 2)

> *"Sometimes we do not aware of 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."* (Engineer 5)

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 the planner."* (Engineer 8)

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."*
>
> (Engineer 1)

Undeniable, using software facilitates design works. Nevertheless, compliance with 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 with the code of practice.

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, it occurs along the way of the design process, mainly when a decision is to be made, to be justified and to be dominating the orientation.

Forming Conjectures/Assumptions

Beginning at the preliminary stage of design, 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 design stage.

> *"Preliminary stage is for preliminary info, and from this stage we could make assumptions on what is going on."*
>
> (Engineer 5)

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 design, 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."* (Engineer 4)

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

> *"…and for this, the 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?"*
>
> (Engineer 3)

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

> *"We do thinking that needs imagination, not like 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."* (Engineer 8)

Forming conjectures is a part of the 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.

> *"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."* (Engineer 1)

Drawing Reasonable Conclusions

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

In the same way, correctly *examining ideas* and *assessing the credibility of statements* for making a decision and justification is 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."* (Engineer 3)

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 a discussion* for coordination prior to 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." (Engineer 7)

In addition, to anticipate any reasonable conclusion or decision, *using evidence to solve problem* reflects a 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 design process.

"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." (Engineer 7)

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 design.

"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." (Engineer 7)

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 the 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." (Engineer 7)

Defending Claims with Good Reasons

Basically, to prioritize safety and minimize cost are the main factors being considered in design projects, 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 design projects.

> *"...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."* (Engineer 1)

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."* (Engineer 8)

As mentioned previously, software facilitates design works. Therefore, most of the 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 design. Again, experience adds some value in this case. When this part is verified, they can defend their claim with good reasons and justification.

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...."* (Engineer 8)

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.

Giving Alternative Ways/Solutions

As mentioned earlier, forming conjectures is one of the processes in justifying decisions reasonably. This process inevitably affects the way they believe and see problems in design. Additionally, when designing a project, their perception of 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 design process. They have to be *flexible in considering alternatives* as a *truth-seeking* practice, complementing their belief in the design 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."* (Engineer 3)

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 the 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 a better way, to *grip with uncertainties*, as well as *giving alternative ways or solutions* to the problems.

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 design process.

> *"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."* (Engineer 7)

Selecting/Pursuing the Right Approach

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

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."* (Engineer 7)

Obviously, the usage of software is dominating and indispensable in design, 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 the design projects. 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."* (Engineer 8)

It can be seen that the design 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 a 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."* (Engineer 7)

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 problems, 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 extend 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…."* (Engineer 1)

CONCLUSIONS

This paper presents an explicit description of the process theory emerged from this study regarding the decision making process in engineering design pertaining to critical thinking and mathematical thinking. The study has identified six essential processes of justifying decisions reasonably in engineering design process, namely complying requirements, forming conjectures, drawing reasonable conclusions, defending claims with good reasons, giving alternative ways and selecting and pursuing the right approach. These six processes were developed from the pertinent elements of critical thinking and mathematical thinking through the multiple stages of analytic process using the analytic tools, namely Conditional Relationship Guide and Reflective Coding Matrix. This study may inform not only engineering education and practicing engineers, but also future researchers who are interested to further investigate the application and interaction of critical thinking and mathematical thinking in engineering practice. This study provides evidence on the usage of both types of 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, to suit the engineering program outcomes. The emerging theory is useful for engineering practice, which is currently still lacking in relation to the engineering design. By recognizing the role of Math-Related Critical Thinking theory in the real engineering practice may help prospective engineers to be better guided on how to engage in these two types of thinking in engineering problem solving and transfer the knowledge material they have learned across the engineering disciplines.

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REFERENCES

BOK2 ASCE. (2008). *Civil engineering body of knowledge for the 21st century: Preparing the civil engineer for the future* (2nd ed.). Reston, Virginia: American Society of Civil Engineers.

Bureau of Labor Statistics, U.S. Department of Labor. (2012). *Occupational outlook handbook, civil engineers*. Retrieved December 7, 2013, from https://www.bls.gov/ooh/architecture-and-engineering/civil-engineers.htm#startcontent

Cardella, M. E., & Atman, C. (2007). Engineering students' mathematical thinking: In the wild and with a lab based task. *Paper presented at 2007 Annual Conference & Exposition*, Honolulu, Hawaii, USA.

Corbin, J., & Strauss, A. (1990). Grounded theory research_procedures, canons and evaluative criteria. *Qualitative Sociology*, *19*(6), 418–427.

Daly, S., Mcgowan, A. R., & Papalambros, P. Y. (2013). Using qualitative research methods in engineering design research. In *19th International Conference on Engineering Design*, Seoul, Korea.

Department of Civil & Environmental Engineering. (2012). What is civil engineering? Retrieved December 23, 2013, from http://www.civil.utah.edu/what_is#skiptarget

Dorward, L. (2013). *What are the most important skills for a civil engineer?* Houston Chronicle, Hearst Corporation. Retrieved August 20, 2014, from https://work.chron.com/important-skills-civil-engineer-6187.html

EAC-BEM. (2012). *Engineering programme accreditation manual 2012*. Petaling Jaya, Malaysia: Engineering Accreditation Council, Board of Engineering Malaysia.

Engineering Accreditation Commission. (2014). *2015-2016 criteria for accrediting engineering programs*. Baltimore, USA: ABET.

Facione, P. A. (1990). *Critical thinking : A statement of expert consensus for purposes of educational assessment and instruction*. Millbrae, USA: The California Academic Press.

Facione, P. A. (2007). *Critical thinking : What it is and why it counts*. Millbrae, USA: The California Academic Press.

Facione, P. A. (2013). *Critical thinking : What It is and why it counts*. Millbrae, USA: The California Academic Press.

Facione, P. A., Facione, N. C., & Giancarlo, C. A. (2000). The disposition toward critical thinking : Its character, measurement, and relationship to critical thinking skill. *Informal Logic*, *20*(1), 61–84.

Felder, R. (2012). Engineering education: A tale of two paradigms. In B. McCabe, M. Pantazidou, & D. Phillips (Eds.), *Shaking the foundations of geo-engineering education* (pp. 9–14). Leiden, Netherlands: CRC Press.

Jonassen, D. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, *48*(4), 63–85. doi:10.1007/BF02300500

Khandani, S. (2005). Engineering design process: Education transfer plan. Retrieved February 13, 2014, from http://www.saylor.org/site/wp-content/uploads/2012/09/ME101-4.1-Engineering-Design-Process.pdf

National Academy of Engineering. (2005). *Educating the engineer of 2020: Adapting engineering education to the new century*. Washington, USA: National Academies Press.

National Academy of Engineering. (2012). *Infusing real world experiences into engineering education*. Washington, USA: National Academies Press.

Nelson, E. A. (2012). What makes an engineer an engineer? In *Structures Congress 2012 © ASCE 2012* (pp. 1152–1159). Rhodes Island, Greece: Structures Workshop, Inc.

Osman, S., Abu, M. S., Mohammad, S., & Mokhtar, M. (2015a). Integrating pertinent elelments of critical thinking and mathematical thinking used by practicing civil engineers in grounded theory analysis. *Journal of Social Sciences Research*, *8*(3), 1641–1650.

Osman, S., Abu, M. S., Mohammad, S., & Mokhtar, M. (2015b). Interrelation among pertinent elements of critical thinking and mathematical thinking in the real-world practice of civil engineering. *Malaysian Journal of Civil Engineering*, *27*(2), 290–304.

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.

Osman, S., Mohammad, S., & Abu, M. S. (2015). A preliminary study on the integral relationship between critical thinking and mathematical thinking among practicing civil engineers. *AIP Conference Proceedings*. Penang, Malaysia: AIP Publishing LLC. doi: 10.1063/1.4915748

Schoenfeld, A. H. (1985). *Mathematical problem solving*. Orlando, USA: Academic Press, Inc.

Schoenfeld, A. H. (1992). Learning to think mathematically: Problem solving, metacognition, and sense-making in mathematics. In D. Grouws (Ed.), *Handbook for research on mathematics teaching and learning* (pp. 334–370). New York, USA: MacMillan.

Scott, K. W., & Howell, D. (2008). Clarifying analysis and interpretation in grounded theory:

Using a conditional relationship guide and reflective coding matrix. *International Journal of Qualitative Methods*, *7*(2), 1–15.

Strauss, A., & Corbin, J. (1990). *Basics of qualitative research: Grounded theory procedures and techniques*. Newbury Park, USA: Sage Publications, Inc.

Strauss, A., & Corbin, J. (1998). *Basics of qualitative research: Techniques and procedures for developing grounded theory* (2nd ed.). Thousand Oaks, USA: Sage Publications, Inc.

Suddaby, R. (2006). From The editors: What grounded theory is not. *Academy of Management Journal*, *49*(4), 633–642. doi: 10.5465/AMJ.2006.22083020

Thornberg, R. (2012). Informed grounded theory. *Scandinavian Journal of Educational Research*, *56*(3), 243–259. doi: 10.1080/00313831.2011.581686