Math-oriented critical thinking elements for civil engineering undergraduates: are they relevant?

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ABSTRACT

For years, mathematical thinking and critical thinking have been regarded as integral components of engineering learning. The mathematical thinking has been used as an essential learning tool to facilitate the learning of hardcore engineering subjects whilst critical thinking forms an important attribute among engineering graduates. Findings from an initial study conducted by the authors on a group of practicing civil engineers at a civil engineering consultancy firm in Malaysia on the nature of workplace problems seem to suggest a co-existence of a close congruence between these two perspectives of thinking. These findings lead to the critical review discussed in this paper on the possibility of a close congruence (simply called MOCT) between critical thinking perspectives and mathematical thinking perspectives in civil engineering. This paper also discusses the rationale and the conceptual framework of an ongoing study into the nature of congruence between these two perspectives among the students during the civil engineering design activities at Universiti Teknologi Malaysia (UTM). A clearer understanding of such congruence is expected to provide additional dimension of the role of mathematics learning in the civil engineering programme.

Keywords: *Elements of critical thinking, mathematical thinking perspectives, math-oriented critical thinking elements.*

INTRODUCTION

The integral relationship between mathematics and civil engineering has long been established. This relationship has developed tremendously over time to the extent where the symbiosis between mathematics and civil engineering is so well established that the complexities of problems in the civil engineering world would demand new theories and approaches in mathematics be explored and developed. This integral relationship has recognized mathematics as a significant tool to solve engineering problems. In fact mathematical thinking has been used as an essential learning tool to facilitate the learning of hardcore engineering subjects.

The American Society for Civil Engineering in the body of knowledge (ASCE, 2008) has explicitly noted mathematics as one of the four foundational legs which supports the future technical and professional practice education of civil engineers. Whilst this indicates the imperative significance of mathematics in civil engineering, the reports of Engineer 2020 (NAE, 2004 & 2005) and the Millennium Project (Duderstadt, 2008) reveal critical thinking as an essential elements of the key attributes of an engineer.

The current situation has caused a deep surge of interest to yet better incorporate critical thinking in the curricula at all levels in educational institutions. Educational systems in North America, the UK (Bailin, Case, Coombs and Daniels, 1999) and in Asia Pacific countries, such as Singapore (Goh, 1997) and Australia (Victoria, 2006) have embarked on reforms in which critical thinking is placed as a key component of their educational objectives. Similarly, the Engineering Accreditation Council for the Board of Engineers of Malaysia too has emphasizes on critical thinking skills development, and evidence-based decision making in the curriculum (EAC|BEM, 2007).

Despite the important demand for mathematics and the significant urge for critical thinking in many engineering programs, a review into the body of knowledge for the ASCE (ASCE, 2008) reveals no clear descriptions delineating critical thinking elements for the mathematics course in civil engineering. This unfortunate situation can lead to difficulties in communication between those who need to be absolutely clear amongst themselves about the standard of an engineering graduate at the end of the degree program (Engineering Professors Council, as cited by Maillardet, 2004). Facione et. al., (1995) express concern that it would be impossible to understand the teaching of critical thinking without an appreciation of the characterological profile of the kind of individual one was trying to nurture.

This imperative need to be both mathematically and critically competent has led to research to explore and examine the proximity of these two perspectives of thinking as a two-dimensional *math-oriented critical thinking* (simply called MOCT) elements among civil engineering undergraduates. Less technically, MOCT is operationally defined as a continual process that involves acquiring and using an appropriate set of math-related cognitive skills. These skills are affectively driven by dispositions that promote and reinforce such skills (Facione, 2007) which also include having the right belief about mathematics and its applications.

TRENDS AND CHALLENGES OF WORKPLACE PROBLEMS

An initial exploration at a civil engineering consultancy firm in Kuala Lumpur, Malaysia was undertaken to get an overview of the nature of civil engineering workplace problems and the math-related skills involved in solving these problems. Interviews and observations were carried out on a group of practicing civil engineers of this firm at various occasions - at the firm's office during their design work stage, at construction sites and in their technical meetings (Radzi et al., 2010).

Interviews were semi-structured with questions focused on the overview of the stages involved in projects, general questions about their experiences relating to challenges, constraints and difficulties encountered, the mathematical aspects such as variables considered, establishing relationship between these variables, mathematical approaches applied in their design drawings and overall solutions to solving their engineering problems.

Some prevalent trends and challenges of civil engineering workplace problems in their real contexts were noted. These themes and categories include workplace problems which are not well defined, workplace problems that encompass non-engineering parameters, problems which are solved by common Code of Practice, problems that encounter unanticipated challenges, problems that essentially require collaborative effort with other sectors to solve and the need for engineers to rely on their past experiences to solve problems (Radzi et. al., 2010).

Close observations of the practicing civil engineers at this firm seem to significantly indicate that relevant mathematical analysis may be called for to solve their civil engineering tasks. For example, the study reveals that in assessing risks, a civil engineer would be concerned with the accurate safety factor in all structural constructions, their mathematical calculations and interpretation of results during the process of design analysis has to be within the accurate range to avoid any fatal injuries (Radzi et al., 2010). Similarly, research done by Gainsburgh (2003) shows strong indications that structural and civil engineers significantly deal with units, quantities and procedures where mathematical modeling is a salient feature.

In most of the themes identified, mathematics is widely applied in civil and structural engineering problems. Although the 'pure' mathematical meanings seem to be implicitly hidden and embedded behind the 'civil and structural feel' of the problems, it still remains relevant to know where analytical results come from. The expressed clusters of responses seem to suggest that a strong desirability of acquiring the merits of both the mathematical thinking and critical thinking abilities would be essential to support the analytical ability of civil engineers, to increase their ability to interpret, evaluate and integrate results, and thus increase the sophistication of their decisions on well informed arguments.

IS MOCT RELEVANT IN CIVIL ENGINEERING? A CRITICAL REVIEW

One important emphasis Schoenfeld (1994) has noted is, "doing mathematics" is a social act where individuals need to interact with each other, thus they need to rely on their communicative abilities. For example, many real world problems can well be represented by mathematical models as a way of seeing, analyzing and solving. However, the practical use of these conceptual models to predict results will inevitably require some analysis of errors or uncertainties. So when groups of individuals are engaged in mathematical modeling say, these individuals interact in a kind of communicative ways in generating ideas, negotiating the analysis of their results especially with regards to errors or uncertainties, developing ways to solution and having to present their reasoning in the form of arguments.

Reflecting on the initial work done on practicing civil engineers at the observed firm during the construction of the double track railways, findings reveal the essential interactions and collaborations between civil engineers and people from other sectors. The mathematical terms and calculations involved also reveal the essential of mathematical analysis in their work (Radzi et al., 2010). So when people interact the following communicative behaviors may come into play such as having to describe methods and results, justify procedures or arguments, and propose and defend with good reasons one's points of views or analyses.

In the construction of the double track railway, cautious consideration has to be taken care of so that the swing bridge which is in operation for transport purposes across a wide river in Prai, Penang, Malaysia, does not "touch" the railway tracks under construction (Radzi et al., 2010). Undoubtedly, the civil engineers need to produce sound mathematical analysis to obtain the safe range for the bridge and the tracks. Other findings reveal that in assessing risks, a civil engineer would be concern with the accurate safety factor in all structural constructions, their mathematical calculations and interpretation of results during the process of design analysis has to be within the accurate range to avoid any fatal injuries (Radzi et al., 2010).These are among the many indications that civil engineers are indeed "*mathematically-oriented community*".

Thus, Schoenfeld's idea of "doing mathematics" seems to suggest a significant congruence with Facione's critical thinking skills when Facione (2007) included the ability to present in a cogent and coherent ways the results of one's reasoning and to state and to justify that reasoning in the form of cogent arguments as essential critical thinking elements of explanation. The training of civil engineers should provide environments where reciprocal interactions among students can lead to both consequences of mathematical thinking and critical thinking.

Schoenfeld (1985) includes the abilities to produce mathematical arguments as relevant competencies. As technological experts, civil engineers would rely on these relevant competencies to produce strong mathematical analyses that can for example, exactly predict the behavior of beams as expected. This again appears to be congruent with the critical thinking perspectives of Facione (2007) when he noted on the need to provide justifications for procedures used and results obtained to problems solved.

Other findings of the initial work too sseem to indicate that the ability to mathematically analyze and interpret data are much valued (Radzi et al., 2010). Schoenfeld (1992) noted that such abilities would entail making informed judgments on the basis of those interpretations. Whilst analysis and interpretation are amongst the two main cognitive skills of critical thinking proposed by Facione (2007), it reflects on the significance to train our prospective civil engineers to think both mathematically and critically or simply to acquire the MOCT elements to facilitate the process of solving civil engineering problems.

A glance at the Engineers 2020 (NAE, 2005), and one would notice the significance of possessing strong analytical skills as the first key attributes listed to support success of engineering profession in 2020 and beyond. Being one of the major critical thinking skills, strong analytical skills which employ the principles of mathematics (NAE, 2005) besides others, further highlights the close affinity of critical thinking with mathematical thinking in achieving the key attributes outlined by Engineers 2020. In fact, many of the attributes listed by the Engineers 2020 (NAE, 2005) indicate close proximity to the applications of mathematical knowledge and skills. In these particular attributes, the engineers need to engage themselves mathematically either to define and formulate their engineering problem, model the problem, solve the problem, evaluate, analyze and interpret the results.

Although the language of mathematics is based on rules that must be learned, it is important for motivation that students move beyond rules to be able to express things in the language of mathematics (Schoenfeld, 1992). Imposing these situations on our students would imply that allowing them to think mathematically would provide them with the opportunity to be analytical, both in thinking issues through themselves and in examining the arguments put forth by others.

ONGOING RESEARCH ON MOCT

Why This Research

The second phase of research on MOCT among prospective civil engineers at UTM is motivated by findings from the initial research done at the civil engineering consultancy firm. This ongoing research on MOCT is also informed and motivated by reports, theories and research relating to preparing future engineers as reported by the National Academy of Engineering (NAE, 2004; 2005), the Royal Academy of Engineering (Spinks, 2006), and the Millennium Project (Duderstadt, 2008).

The world today is facing fast technological innovations and reciprocal social challenges such as information and communication technology explosion, cyber crimes, health and increasing fatal diseases, threatened national security to the extent of using sophisticated war artilleries which cannot distinguish between the targeted and the innocence. As time passes our engineers will have to face even bigger challenges which would require them to solve not only local problems but as well global problems of unprecedented magnitude and scope.

A glimpse of what the engineers need to be able to do in the coming years can be found in the reports of Engineer 2020 (NAE, 2005) and the Millennium Project (Duderstadt, 2008) which reveals the essentials of critical thinking elements well embedded in the key attributes of an engineer. As problem solvers, civil engineers are expected to possess strong analytical skills, exhibit practical ingenuity, master the "tools of the trade" of business and management, understand the principles of leadership, dynamic, able to adapt to changes, and able to apply knowledge and skills to new problems and new contexts (NAE, 2005; Duderstadt, 2008).

Mathematics will be further brought to the forefront when coming to terms with such technological advancement. Consistently Schoenfeld (1992) noted the experience with mathematical modes of thought that develops mathematical power – a capacity of mind of increasing value in this technological age that enables one to read critically, to identify fallacies, to detect bias, to assess risk, and to suggest alternatives. Thus, fluency with mathematics is an essential tool in the modern graduate civil engineers. In order to align with the future transformation of engineering education for the 21st century, a conscious and sustained effort is needed to bring forth the awareness of the profound relevance of producing mathematically and critically competent prospective civil engineers.

Thus, the current research will objectively explore the nature of interactions between prevalent elements of critical and mathematical thinking perspectives during the design activities among civil engineering students at UTM. The findings will give a deeper and broader insight into mathematics and civil engineering communities, of the new dimension mathematics can play in shaping the critical thinking abilities among the engineering students. This may also have significant pedagogical impacts in the way mathematics is taught to the students.

The Underlying Framework - Critical Thinking Perspectives

While the views of other proponents of critical thinking are not to be denied, this research draws upon the critical thinking perspectives described by Facione et. al. (1990, 1995 & 2007). Although these sets of critical thinking skills are non-content specific, but they do offer close congruency to the general standards of achievement of engineering graduates as outlined by local and abroad engineering bodies and accreditation councils such as the Accreditation Board of Engineering and Technology, USA, (ABET, 2000), American Society of Civil Engineers (ASCE, 2008), the Engineering Professors Council, UK, (Engineering Professors Council, as cited by Maillardet, 2004), and Board Engineers of Malaysia (BEM, 2007).

Being closely congruent to the general standards of achievement of engineering graduates, these sets of critical thinking skills are also in close proximity to the Bloom's Taxonomy which provides a comprehensive body of knowledge outcome rubric (ASCE, 2008) for civil engineering. In defining the outcome rubric, Bloom's six levels of cognitive development were referred to without modification as levels of achievement (ASCE, 2008).

Being entrusted with the progressive well-being of humanity in creating, improving and protecting the environment, in providing facilities for community living, industry and transportation, and in providing structures for the use of humanity (ASCE, 2008), civil engineers may expect to encounter decisive roles and situations and inevitably haveto make decisions. For example, for many construction disasters civil engineers would be among the first key technical experts called for to give professional opinions and constructive suggestions to correct and eventually evade such engineering frailties in the future.

Compounded by the challenge that engineering practice will need to shift from traditional problem solving and design skills toward more innovative solutions (Dudderstadt, 2008), the training to be able to think critically should be well grounded within the civil engineering undergraduates as they would one day make up the important productive units in our society's work force. The critical thinking abilities of a civil engineer would allow a far more holistic approach to addressing these social needs and priorities of socio-civil engineering problems.

Facione et. al's. (1990, 1995 & 2007) included the following as cognitive dimension of the critical thinking skills; *interpretation, analysis, evaluation, inference, explanation, self-regulation.*

The Underlying Framework – Mathematical Thinking Perspectives

Schoenfeld distinguishes five "aspects" of mathematical thinking: (1) resources - the mathematical knowledge possessed by the individual that can be brought to bear on the problem at hand, (2) problem solving strategies or heuristics, (3) monitoring and control (mechanisms to regulate the use of cognitive structures, such as memory), (4) beliefs and affects (about mathematics), and (5) engagement in mathematical practices.

“Resources" describes our current understanding of cognitive structures: the constructive nature of cognition, cognitive architecture, memory, and access to it. "Heuristics" describes the literature on mathematical problem solving strategies. "Monitoring and control" describes research related to the aspect of metacognition known as self-regulation. "Beliefs and affects" considers individuals' relationships to the mathematical situations they find themselves in, and the effects of individual perspectives on mathematical behavior and performance. Finally, "Practices" focuses on the practical side of the issue of socialization; describing instructional attempts to foster mathematical thinking by creating microcosms of mathematical practice (Schoenfeld, 1992, pp. 5).

THE METHODOLOGY

This study focuses on the critical thinking perspectives and mathematical thinking perspectives of civil engineering students during their civil engineering design activities. According to Johnson & Christensen (2000) it is the “inner worlds or the subjective worlds” (Johnson & Christensen, 2000) of an individual; the values uphold, beliefs, thoughts and attitudes that strongly shape and influence their observable practices. The best approach to gain access to this intimate domain of data is through a close-up observation and inquiry. Thus a qualitative nature of study is the best way of representing the multiple realities and experiences of the civil engineering students working through their civil engineering design activities.

Indwelling as close to the construction of the real world of civil engineering students helps increases the exposure and getting a better picture of the cognitive and behavioral aspects during their civil engineering design activities. These observations serve two purposes; firstly to counter check the claims and reports students made regarding their engagements with mathematical thinking and critical thinking in their problem solving activities through interviews made prior to the start of their design activities, and secondly to facilitate preparing the appropriate questions for interviews at later stages of the research. Questions through critical incidence technique are formulated and short field notes were noted down to help provide further information as the observations and interviews are carried out. A few students who fulfilled a certain set of criteria are selected for this purposeful sampling.

Adhering to Corbin’s advice (Corbin and Strauss, 2008), the researcher needs to feel the experiences through the eyes of these participants. These close-up observations and inquiries would help the researcher to develop a better understanding of the broader social context of human mental processes and their situated features (Corbin and Strauss, 2008). Semin (in Lave and Wenger, 2003) coherently noted that an understanding of human cognition and cognitive processes cannot be explored in a framework that detaches mental activities from the socio-cultural settings of the participants.

Interviews are semi-structured with open ended questions. Post interviews are follow-up steps to the observations for purposes of further clarifications or confirmations. All interviews are recorded using a digital audio recorder and transcribed verbatim.

DISCUSSIONS AND CONCLUSIONS

A clearer understanding of congruence between mathematical thinking and critical thinking is anticipated to provide additional dimension of the role of mathematics learning in the engineering programme. The current phenomena has placed mathematical practices which includes teaching and learning mathematics and consequently mathematical thinking and critical thinking a new premium of being challenged to shift from the traditional mode of teaching and learning mathematics as a separate entity toward more innovative ways weaved in the actual civil engineering problem solving activities and design skills. The shift should be broadly focused on the development of students as emerging professionals as well as on the subject content. Students should be made to feel the relevance of mathematical knowledge and skills and hence the mathematical thinking and critical thinking in the learning of mathematics, for example by introducing mathematical concepts in the contexts of civil engineering applications.

Certainly, we believe that placing mathematical thinking and critical thinking as a two dimensional perspective weaved together, within the context of solving civil engineering problems is one way of approaching ABET's engineering criteria for mathematical and engineering knowledge (3.a), analyzing and interpreting data (3.b), and formulating and solving engineering problems (3.e) in a course with significant technical content. Thus a study to identify the elements of MOCT skills which would interweave both the critical thinking and mathematical thinking perspectives related to the cognitive activities and prevalent behavioral activities of civil engineering students during their engineering design activities would be relevant and significant.

Early findings of this second phase of the research seem to confirm the feasibility and significance of MOCT elements among the civil engineering students during their civil engineering design activities. However, further results have yet to be analyzed, discussed and disseminated later on.

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