Developing "Critical Thinking Skills" in Graduate Engineering Program

Dr. Shekar Viswanathan, National University

Dr. Viswanathan is a Professor at the Department of Applied Engineering at National University, California. Dr. Viswanathan is an educator, researcher and administrator with more than twenty-five years of industrial and academic experience encompassing engineering and environmental consulting, research and development, and technology development. Career experience includes teaching at the University level, conducting fundamental research, and developing continuing educational courses.

Mr. Ben D Radhakrishnan, National University

Prof. Ben D Radhakrishnan is the Lead Faculty for MS Sustainability Management Program in School of Engineering and Computing at National University, San Diego, CA. He develops and teaches Engineering and Sustainability Management graduate level courses. Ben has conducted Sustainability workshops in Los Angeles (Army) and San Diego (SDGE). His special interests and research include promoting Leadership in Sustainability Practices, energy management of Data Centers and to establish Sustainable strategies for enterprises. He spent part of his 2011 and 2012 summers as an Affiliate Researcher at Lawrence Berkeley National Laboratory, Berkeley, CA, focusing on the energy efficiency of IT Equipment in a Data Centers, and continues this work as a Consultant.

Prof. Radhakrishnan has presented papers in conferences in Lima, Peru, Florianopolis, Brazil, Pondicherry, India, and Indianapolis, IN – all topics related to Sustainability. His most current research topic includes Resilient Sustainable Urbanization and 'gamification' in teaching Sustainability.

Prof. Radhakrishnan got his first Master's, M.Tech, from the Indian Institute of Technology, Chennai, India. He also has MS from SUNY Buffalo, NY, M.B.A, and Sustainable Business Practices Certification from UCSD. Ben's hobbies include Photography & Videography, travelling and hiking.

Developing "Critical Thinking Skills" in Graduate Engineering Program

ABSTRACT

This paper provides a review of two programs incorporating "critical thinking skills" as a major focus. In addition, this paper illustrates examples of structured assignments and novel exercises that were developed and implemented to promote "critical thinking skills." Also, special rubrics developed to measure "critical thinking skills" are illustrated. This paper describes Student Centric Learning (SCL) with its four categories of implementation. It also demonstrates that SCL is a strong enabler for developing, implementing, and instilling critical thinking skills. Based on the findings, that gamification along with SCL with its four categories of implementation really form the four pillars and serves as a strong enabler for developing, implementing, and instilling critical thinking skills.

Introduction

"Critical Thinking Skills" from an engineering context can be defined as the graduate attribute developed through a structured process of applying, analyzing, synthesizing, and evaluating data/information. The metacognitive ability involving perception, critique, judgment, and decision making, allows students to orchestrate and self-regulate their own learning strategies and those abilities encompassed in the term 'critical thinking.' It is an important skill that accrediting bodies and engineering employers consider as a must for engineering graduates. However, the process of achieving critical thinking skills is not always well laid out and /or developed. Although a number of models have been developed in this topic by many academics, developing "critical thinking skills" can be a long and arduous process. In particular, the development of higher education program level critical thinking skills require detailed course level planning, structured assignments, critical analysis of case studies, student centric learning, and guided design using tools such as simulation and gaming, communication exercises, and laboratory experiments. Research suggests that the development of *any* skill is best facilitated by practice and not by demonstration. Students acquire skills most effectively through practice and feedback. Relying solely on teaching approaches such as problem based learning are unlikely to

help students to develop critical thinking skills. In addition, emphasis should also be given to the assessment and evaluation of critical thinking skills.

This paper provides a review of the Master of Science in Engineering Management and Sustainability Management programs, both of which were designed to incorporate "critical thinking skills" as a major focus. In addition, the paper illustrates examples of structured assignments and novel exercises that were developed and implemented to promote "critical thinking skills." In addition, special rubrics developed to measure "critical thinking skills" are illustrated.

Background

One of the key primary goals of engineering schools for some time has been to develop, promote, and instill "critical thinking" skills in engineering students. The National Academy of Engineering[1] has clearly identified the need to train engineers in critical thinking by exposing them to stimulating exercises involving real-world environments. Critical thinking is considered as a resilience factor in engineering programs[2]. It causes individuals to analyze causes and responsibilities. Resilience skills development is defined as "the individual's ability to identify and solve problems," in ways that it would impact his/her own transformation and growth[3]. Developing resilience depends on cultivating those skills through exercises that stimulate critical thinking and strengthen students' analysis and decision-making capabilities. Well-designed problem-based courses are likely to encourage learners to think critically about content since courses start with problems rather than with a program of lectures and tutorials aimed at teaching students a body of knowledge[4]. Woods et al.[5] found that transmitting knowledge was the easiest part of teaching; it was the task of equipping students with the critical skills they need to succeed as professionals and responsible members of society that he found to be more challenging.

Student Centric Learning (SCL) method of teaching where the students are heavily engaged in the class can provide an excellent platform to develop critical thinking skills. Through SCL, the instructor (who acts more like a coach) takes the responsibility to bring in real-world problems to solve. At the senior or graduate level classes, the students are also encouraged to bring their own work-place sample problems and solve them using the SCL method.

Inter-Connectivity between Critical Thinking and SCL

Some of the key principles included in the definition of critical thinking by National Council of Excellence are the following (http://www.criticalthinking.org):

- Active and skillful conceptualization
- Analysis, synthesis, and evaluation
- Observation, experience, reflection, reasoning and communication
- Clarity, accuracy, and precision
- Relevance, sound evidence, and fairness

Many, if not all the SCL practices/methods, support and demonstrate one or more of the above principles. The Council on Science and Technology at Princeton University has identified several methods of Student-Centered Teaching methods (also referred to as Student Centric Instruction, SCI). These methods range from small group discussions to case studies to computer simulations and games (or ***gamification***: *the process of learning through games; referring to the design/creation, play and demonstrating a game in support of course learning outcomes*). The objective of each of these practices or techniques is to engage the student so that he/she participates in *active* and not *passive* learning (referring to the traditional lecture with practically no interaction with the instructor or among the students). When SCL is properly implemented, it can lead to increased motivation to learn, greater retention of knowledge, deeper understanding, and more positive attitudes towards the subject being taught.

One of the key reports released by the National Research Council[6] recommended that learning environments can be organized into the following different categories or focus areas: knowledge-centered, learner-centered, assessment-centered, and community-centered. Knowledge-centered learning mainly refers to the students' ability to transfer their learning to critical thinking and problem-solving skills; the learner-centric approach refers to the ideas and information the students bring on their own from their prior learning or other experiences; the assessment learning approach gives the students a quick feedback on how the students meet the course learning outcomes and what they need to do to improve (or turn around); the community-learning approach refers to the opportunities that help promote interactions among students and thus provide them with opportunities to learn from each other. This not only gives each student the opportunity to become a teacher under this category, but it also helps foster communication and teamwork.[7]

The key attributes of Student Centric Learning and its associate processes or methods of implementation are the following:

- The focus is both on the students and instructor as it also allows for a high degree of interaction between students and the instructor
- Students work in teams or alone depending on the purpose of the activity
- Students actively participate in class discussions while the instructor facilitates by initiating a class dialogue with an open ended topic or a question
- Students choose or initiate topics for discussion

By comparing the definition of critical thinking listed above and the SCL attributes, processes, or methods, it clear that there is a great inter-connection and association between the two. SCL implementation is an effective way of developing, promoting, and instilling critical thinking for engineering students.

Implementation of Advanced Practices of SCL to Develop Critical Thinking Skills

The SCL practices that help influence the development of critical thinking fall within the four categories (or pillars): Knowledge-centric, Leaner-Centric, Assessment Centric and Community Centric[4]. Specific practices implemented for three categories which are directly or indirectly related to critical thinking, namely Knowledge-Centric, Leaner-Centric and Community Centric, will be discussed. Different SCL activities will be discussed first followed by students' feedback.

Knowledge-Centric SCL

The main learning base here is to focus on developing critical thinking and data synthesis. Two practices have been implemented for this SCL – '*News of the Day'* and '*Debates.'*

In the first activity, '*News of the Day,'* onsite students in the different courses participate. The objective is to identify a recent development in the news media or an event that occurred within the last 30-45 days, from any relevant and reputed magazine or newspaper or journal. The news item or event should be directly related to and should meet one or more course objectives. Each student will Open the URL link and present the topic to the class for 5 minutes – what, when, where, its impact as it relates to the course learning outcome. This will be followed by a brief Q&A session. Students are assigned grades for participating in this activity. Each student has to complete the following tasks: identify the source and event (or news), the location of the event/news, how is the event/news tied to the current course, and what is the importance of the news/event. The student will also have to discuss *quantification* as applicable to the subject matter being taught. Students are also expected to interpret the news or event as they see it and give their opinion (positive or negative). As noted, this is an exercise in critical thinking and data synthesis (students can discuss other related events). The instructor publishes a schedule for all students. The *News of the Day* discussion is at the beginning of each class (two or three students

present in each class). This approach ensures that the students are from the beginning of the class active, attentive and engaged.

The '*Debate'* SCL activity is implemented in the Globalization class where teams (or individuals) take a position on whether globalization is 'good' or 'bad' (this is an important topic in today's world). They present their case with a current example and quantification to the class. This is followed by a brief Q&A session. This activity also engages students quickly into the discussions as they often try to bring up related events/situations from their own companies for discussion.

Although text books these days come up with new editions more often than before, this SCL activity keeps the students informed about the latest happenings in the subject they are learning. Students' feedback comments reflect that they are anxious to hear about the latest developments as they come to each class – they have a different expectation at the beginning of each class.

Learner-Centric SCL

The main learning base here is focused on learners becoming 'creators.' The emphasis is on their coming up with new ideas, so as to help advance creativity/innovation. Students are encouraged to use any and all prior knowledge they have into the learning process. Creativity (or *creative thinking*) is sometimes argued to be different from critical thinking. At the same time, it has also been established that there is a relationship between the two[5]. Learner Centric SCL is generally a team activity that requires the student-teams to design, create, play, and demonstrate a game that is relevant to the subject matter and supports course learning outcomes. In this SCL practice, the course team project will be quantified and demonstrated through a game that the team will design, create, play, and demonstrate. Teams are given full freedom (empowered) to

create/innovate and even to adopt any existing game to suit the project under study. This SCL has been successfully implemented in more than one course in the MS Sustainability Management program. This particular SCL is perhaps one of the most advanced SCL used in the graduate classes since real world problems need to be well understood to be able to bring the concepts down to game objective(s), rules, and winning strategy (games have been used in school education and is well documented). Sustainability topics are somewhat new in higher education and the concepts (such as equity) are difficult concepts for students to understand. But *gamification* helps concretize these abstract concepts and allows for deep learning to take place. Many students bring their prior gaming experiences into the *gamification* process, and they help others who may not have that experience by teaching them. The pedagogical role that games in education play to improve critical thinking skills has been well documented[6].

In a *gamification* approach, student engagement, teamwork, innovation, and competitiveness come in to play. Students have to do significant research to come up with game rules and to quantify the subject matter. Since everyone is actively involved or engaged in one or more aspects of a game, it results in higher subject matter retention. SCL also makes learning *fun* and provides opportunities for students to learn additional tools (e.g. Game board design). Due to the success of this approach, it has been implemented in both onsite and online courses.

Assessment-Centric SCL

In addition to the standard assessment tools (e.g. quizzes and exams), this particular SCL approach centers around one or more course homework leading to a specific deliverable from the real world implementation of an advanced topic like ISO14001 Environmental Management System or Renewable Energy Alternatives. Students present both the theory and implementation.

This is a team oriented SCL in line with course learning outcomes. In fact, the students have to come to speed on many of the ISO 14001 standard details on their own (from a secondary text book for the course), research to find an industry implementation that meets the standards, and present it to the whole class. The students are empowered to critique the implementation and recommend changes or improvements to the current implementation. This again is an advanced SCL at the graduate level helping further development of critical thinking skills and students are motivated since it is assessment-centric.

Community-Centric SCL

The focus here is on learners themselves becoming *teachers* to some extent. As a result, it raises the level of mental processing (or learning) and increases interaction among learners. This can be an individual or a team SCL activity. It is recognized that the highest retention (90%) occurs when *teaching others* is involved. This approach puts the students in a different mind-set – a situation where they have to explain and/or answer questions. A teaching SCL activity helps graduate students not only to improve their preparation & presentation skills but also concept-articulation skills. This is very important if they should ever assume a leadership position or even if they have to present to a company C-level management. When a student team prepares a presentation with the idea of teaching the same to their classmates, the approach is thorough with strong team interactions. Idea exchanges and teaching happens. All these inherently increase learning and retention. Research has also established a direct correlation between critical thinking and knowledge retention[7]. These concepts were applied to both engineering management and sustainability management programs.

Master's Degree in Engineering Management

The Master of Engineering Management program (M.S.) is designed to bring the benefits of modern technology and high quality graduate-level instruction to engineers/scientists/technologists interested in furthering their skills in engineering management

In this program, engineering management principles are broadly based and are drawn from many different disciplines such as applied sciences, engineering, natural sciences, mathematics, economics, business, and social sciences.

Master's Degree in Sustainability Management

This program is designed to provide methods and theories appropriate to the study of sustainability from business perspectives to practical engineering. After a comprehensive interdisciplinary introduction to sustainability, students are exposed to managerial key ideas and practices with sustainable perspectives such as risk assessment, life cycle, lean supply chain, firm excellence and innovation.

Engineering Management Program:

In this course, the students were asked to develop a game to illustrate quality and ethical management principles. The following news story was used to develop one such game. Recently, *Los Angeles Times* reported that the USDA is streamlining chicken inspection by cutting 75% of the number of government inspectors (equals to 800 inspector positions) to save the federal government $30 million a year. Recent tests performed at 25 poultry slaughterhouses showed that the reduction in the number of inspectors made very little difference in the detection of salmonella and other diseases. In other words, the more inspection did not equal more quality. The existing rules to increase the production line to move as fast as 140 birds a minute requires four federal inspectors to be positioned along the line. No single inspector inspects more than 35 birds a minute. However, the new relaxed rules would allow lines to speed to 175 birds per

minute while relying on plant employees to spot defective carcasses and pull them from the line. The CDC estimates that there are 1.2 million incidents of salmonella illness each year. Three hundred and eighty two broiler chickens bought from grocery stores tested by Consumer Reports produced 14% salmonella. The union representing poultry workers are concerned with the increased work requirements since the injury rate in this sector exceeds a third higher than the average for all manufacturing industries (59% of line workers already have carpal tunnel syndrome at line speeds of 70 to 91 birds a minute). The students developed an educational game with at least three variables (independent) affecting quality (positive and negative) and ethics. Figure 1 illustrates one such game board. The objective of this game is to "maximize" company profit while improving quality by selecting TQM variable percentages (increasing or decreasing values) for the three independent variables chosen namely, Production Rate, Inspectors, and Employees.

The game is designed with a dice that is electronically rolled (randomness) by pressing the "Roll the Dice Button." The face of the dice is displayed in the "PLAYING AREA." The first roll of the dice represents the Percentage for the three TQM variables (Table 1). The dice is re-rolled twice more to populate the remaining two variables by selecting 'Yes' to the pop-up window. Selecting 'No' re-starts the roll sequence. Figure 2 summarizes the results of the game in the form of a chart that includes Cost/Profit, Ethics, and Quality. The user, through the game play can see the immediate impact of choices selected not only on the total quality and production, but more importantly, on the ethical impact of management choices. The game helps the user with a better understanding of what goes into the decision making process of Total Quality Management, and it allows the user to manage the variables so that the negative impact is minimized and positive impact is maximized.

(Static) Variables	(Random Roll) Percentage	(Player Selection) Positive / Negative	#
Employees	5	Positive	1
	5	Negative	2
	20	Positive	3
	20	Negative	4
Inspectors	5	Positive	1
	5	Negative	2
	20	Positive	3
	20	Negative	4
Production Rate	5	Positive	1
	5	Negative	2
	20	Positive	3
	20	Negative	4

Table 1: TQM Variables Used in Quality Management Game

Once the dice is rolled for all three variables, which are assigned a random (5 or 20) percentage, one must decide whether or not the percentage will be a positive increase or negative decrease of that value. The OK button is selected on the Pop-up to begin positive or negative selection. Once all three variables are assigned a value, the "Ring the TQM Bell" button to "Hit the Striker" is selected and the results are calculated to determine what TQM level one has been achieved. If the choices resulted in a TQM improvement over 30%, the bell will sound congratulating the player on a job well done. The results are evaluated by selecting the "How Well Did You Do" button. This creates the Pareto evaluation charts. After the evaluations are made, the game can be restarted by selecting the "Reset Board" button.

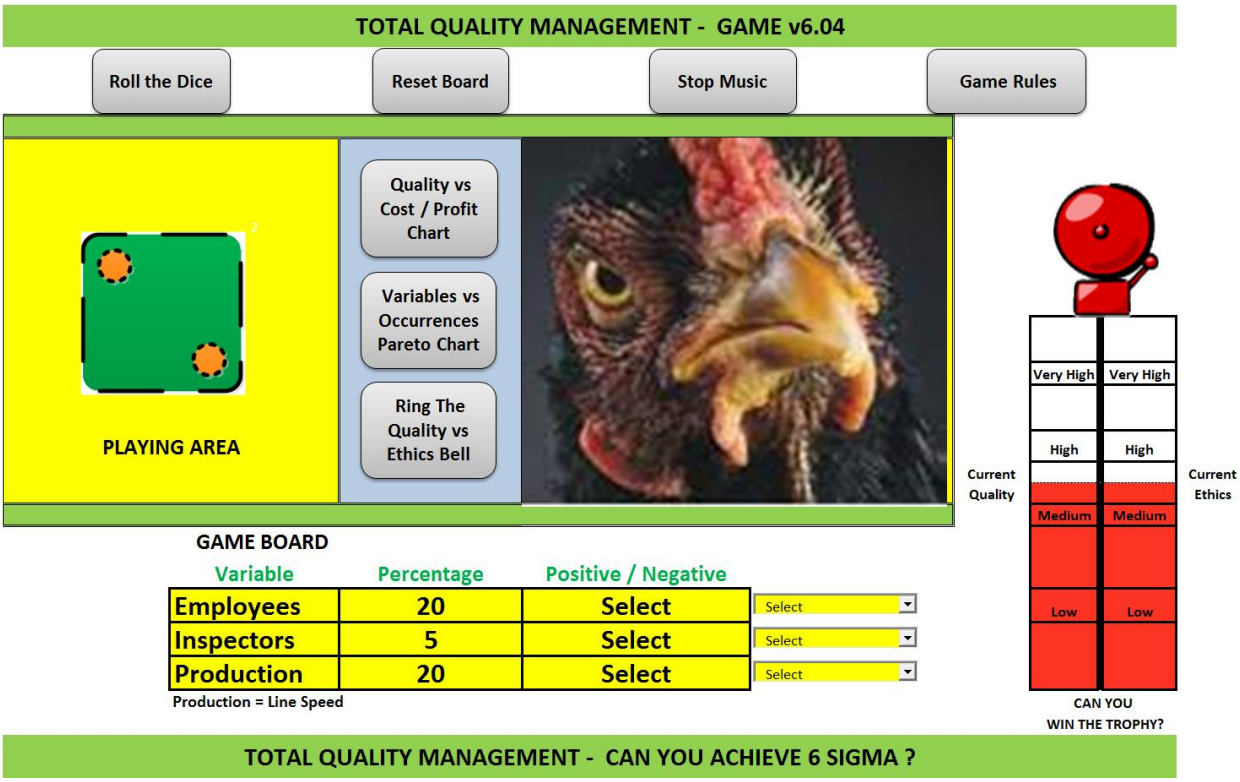

Figure 1: Quality Management Plan Game Board

[Game Design Team: Ali Sultanzai, Rob Walker, John Wandke]

Figure 2: Real Time Dashboard Display showing the Game Outcomes supporting Quality Management

[Game Design Team: Ali Sultanzai, Rob Walker, John Wandke]

This course focused on quality aspects related to project management, operations, and other aspects of engineering. The course covered materials on the theories and principles of total quality management and ethics required for a successful organization. In the example game, the same game topic was given to all the students in the given class. The students were asked to define the problem by considering ethics as one key independent variable. The team that developed the game shown in Figure 1 felt this was one of their best courses both in terms of learning key concepts as well as depth of understanding of the subject matter itself. Figure 3 depicts the students' feedback from the quality management course. The feedback in this course clearly indicates the impact the

game had on students' learning experience and the associated positive impact that the implementation of the game had on the students. The students' input was evaluated on a scale of 1-5 where '5' represents the most favorable feedback. The feedback on the specific student attributes namely innovation, engagement, and learning received a very good rating in this course. The only category that received much less than a 4 was the resource category website. The web site had a few issues including its availability from time to time. Even with this limitation, the students rated this novel game design methodology as being useful in their learning of the subject matter presented to them in this course. This game was developed using standard educational tools such as Excel, and hence the students did not have to spend additional time learning the tools to complete this work.

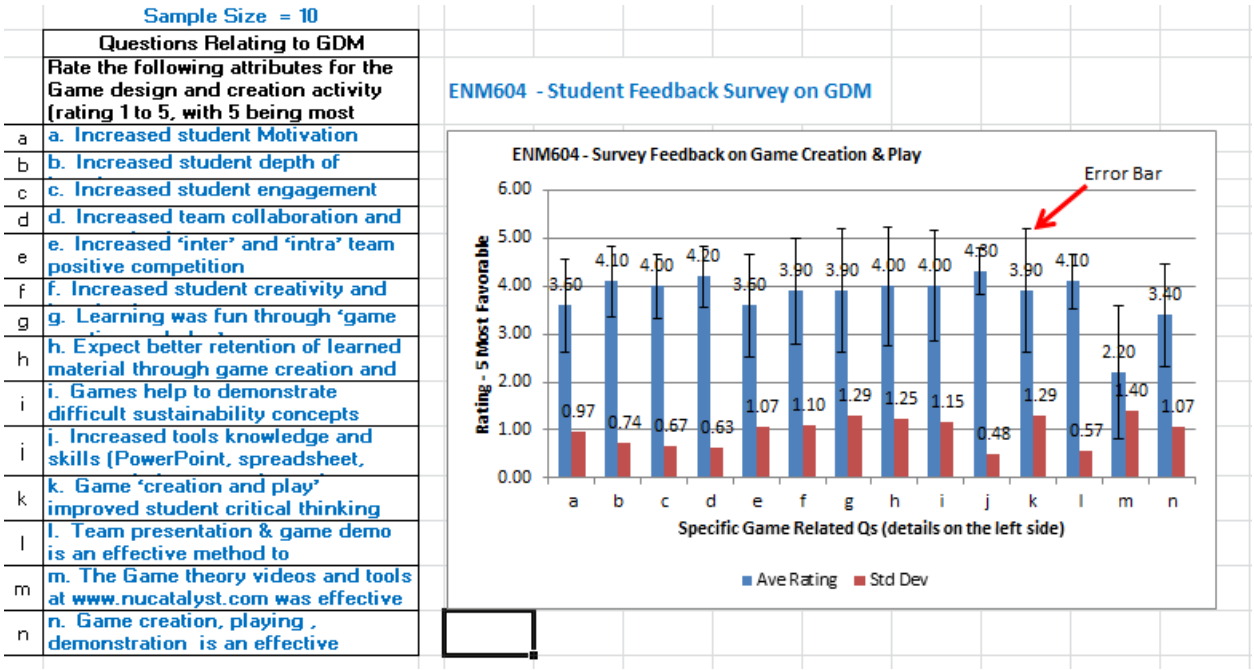

Figure 3: Student Responses from Quality Management Course

Sustainability Management Program:

Three SCL activities that are practiced in this category are the teaching of sustainability principles with an example, implementation of the ice-breaker discussion activity, and giving students the opportunity to select text book chapters to present/teach.

In the first SCL activity, student teams (or individuals) present the theoretical concepts of a sustainability principle (from a secondary course text book): its official name, definition, origin, its specific principles, and an application or implementation that demonstrates the principle. Students need to really think deeply about the sustainability concept and be able to explain as if they are *teachers*. This content is included in their exams.

The second SCL activity, called *icebreaker discussions*, is implemented primarily in the MS Engineering Management course where issues of management and customer relationships as well as their importance are discussed at length. From a process perspective, the class is divided in two sections; one section is the *management* and the other is the *customer* (role playing). The instructor presents a real-life issue and students discuss the issue from the point of view of the role that they are playing. Each section presents a potential solution to the other and negotiates. The roles are switched for another real-life issue so the students get to think beyond theory and to put forward practical solutions. This real live simulation, facilitated by the instructor, promotes management and negotiating skills at the graduate level.

In the third SCL activity in this category, student teams get to pick a chapter of their choice in the primary text book and present it to the class (like teaching, of course) along with a real world example highlighting the theme or core concept of the chapter (e.g. Engineering Ethics). The students also get to vote on what sub-set of these chapters should be included in the exam –

a true democratic process of student empowerment, one that allows them to determine what they are most interested in learning and what they wish to be assessed on.

Student Feedback on SCL Activities

As a part of the initial implementation, it was very important to get students' feedback on these graduate level advanced SCL practices. Surveys were taken at the end of the courses where one or more of these SCL practices were implemented. Students were informed about these activities right in the beginning when they were given the course outline. They were also informed of the assessment points that would be allocated for specific SCL practices (e.g. News of the Day). In these graduate level courses, most of the students are working adults, and so their feedback is very significant and unique. The following charts indicate the feedback from different courses – responses to specific questions asked in each of the courses as it related to SCL practices.

Figures 4 – 6 represent the student feedback on the various categories of SCL practices shown with 1 standard deviation error bars and the sample sizes in each case (5 being the most favorable/highest rating). It should also be noted that the statistical 'mode' for all the feedback received was a 5.

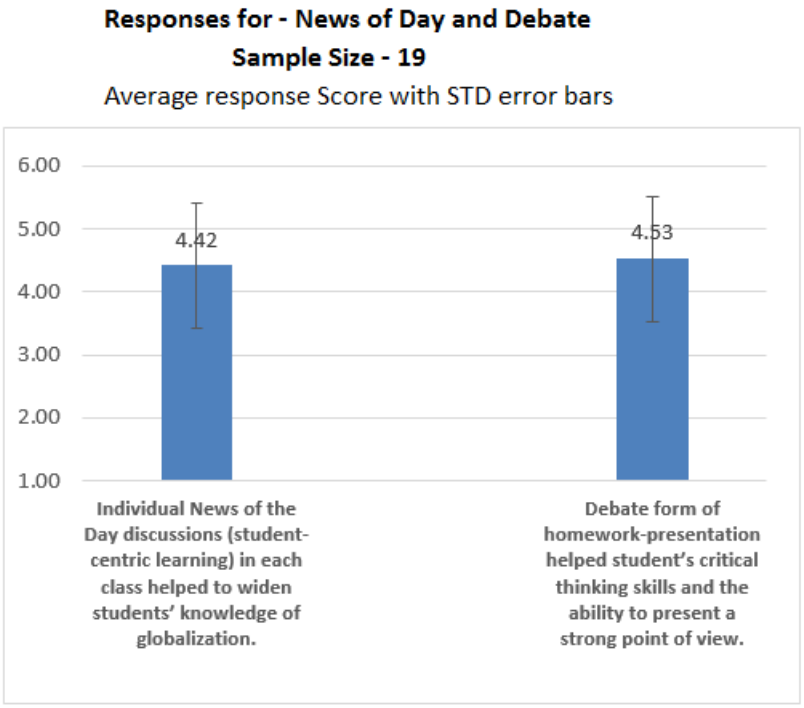

Figure 4: Knowledge-Centric: Student Feedback on '*News of the Day*' and '*Debates*'

Sample Size = 25
Questions Relating to GDM
Rate the following attributes for the Game design and creation activity **(**rating 1 to 5, with 5 being most favorable):
a. Increased student Motivation
b. Increased student depth of learning
c. Increased student engagement
d. Increased team collaboration and communication
e. Increased 'inter' and 'intra' team positive competition
f. Increased student creativity and imagination
g. Learning was fun through 'game creation and play'
h. Expect better retention of learned material through game creation and playing
i. Games help to demonstrate difficult sustainability concepts
j. Increased tools knowledge and skills (PowerPoint, spreadsheet, game website research, etc.)
k. Game 'creation and play' improved student critical thinking skills
l. Team presentation & game demo is an effective method to communicate with the class
m. The Game theory videos and tools at www.nucatalyst.com was effective and useful
n. Game creation, playing , demonstration is an effective method of learning

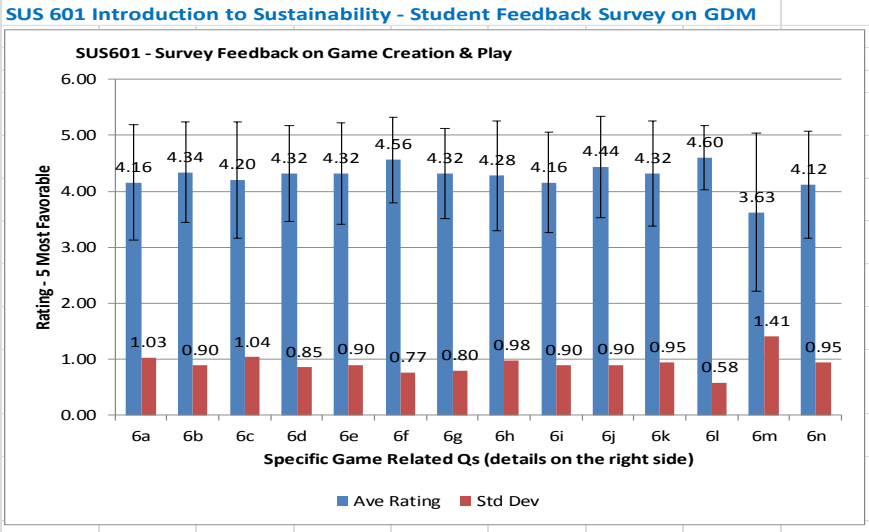

Figure 5 Learner-Centric: Student feedback on an array of Questions for *Gamification*

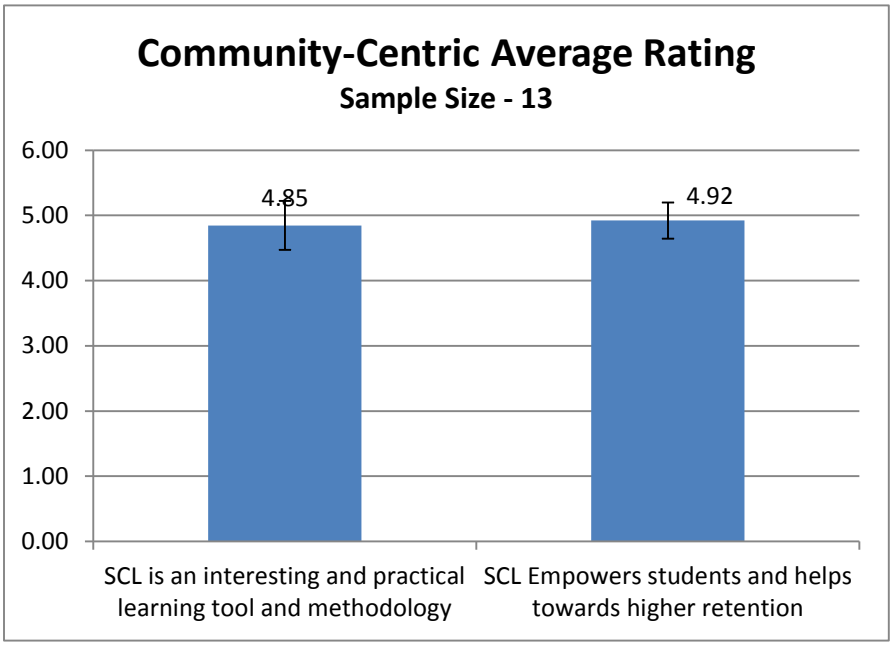

Figure 6: Community Centric – Feedback chapter presentations

Specific questions about the various traits of SCL (e.g. motivation, innovation, etc.) were asked in the *gamification* example (Figure 5). It can be seen that the student feedback is overwhelmingly positive for these traits (all above 4 rating).

As seen from Figure 5, a specific question about SCL helping *critical thinking* had a strong response. It is clear from these figures, the SCL practices were very well received by the students. The students responded to the methodologies adopted with not only very good ratings on the surveys, but also in their comments. More research and data collection would be required to evaluate other variables such as instructors, their teaching style, facilitation, and mediation skills. Another key item to be researched is to check if the students overall do get better grades when these practices are implemented.

Conclusion

It is clear from these findings that the gamification along with SCL with its four categories of implementation really form the four pillars and serves as a strong enabler for developing, implementing, and instilling critical thinking skills. Increased depth of learning, motivation, communication and teamwork were demonstrated through this project. It is evident that the key principles included in *the definition* of critical thinking are strongly supported by the four categories of SCL. SCL exercises described above support the argument that critical thinking is also an intellectual exercise. The assessment part clearly indicated the effectiveness of this gaming approach in learning STEM topics. This approach can be easily extended to other technical courses.

Acknowledgement

The authors wish to express their sincere appreciation to all their students whose cooperation and participation enabled the successful implementation of these activities in various courses.

References

1. National Academy of Engineering, "Educating the Engineer of 2020: adapting education to the new century," National Academics Press. Washington, DC. (2005).
2. Canales Benitez, "Critical Thinking as a Resilience Factor in an Engineering Program,". Creative Education, Vol.4 (2013) No.9, 611-613.
3. Melillo, A., "Resilience and subjectivity," Life cycles. Buenos Aires, Argentina: Paidós Press (2004).
4. Pithers, M.T. and Soden,R., "Critical thinking in education: a review," Educational Research, 42:3, (2000): 237-249.
5. Woods, D.R., Felder, R.M., Rugarcia, A. and Stice, J.E. , " The Future of Engineering Education – Developing Critical Skills", Chem. Engr. Education, *34*(2), 108–117 (2000).
6. National Research Council, "How people learn: Brain, mind, experience and school," National Academy Press, Washington, DC. (1999).

7. Huitt, W., “Critical thinking: An overview,” Educational Psychology Interactive. Valdosta, GA: Valdosta State University (1998). accessed March 9, 2015 http://www.edpsycinteractive.org/topics/cogsys/critthnk.html