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Fostering Mathematical Creativity among Engineering Undergraduates

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Abstract: *This research is used to study engineering undergraduates fostering their mathematical creativity during creative problem solving. This was an exploratory research carried out in a public university as to find out the impact of CPS towards mathematical creativity among the engineering undergraduates. A case study was used to provide deep exploration of how the engineering undergraduates using their creative methods to solve open-ended mathematical problems creatively. Qualitative research design was applied in order to understand in depth the engineering undergraduates working collaboratively to generate their creative ideas during mathematical problem solving. Three final years engineering undergraduates took part in the study. They had to use their divergent and convergent thinking to generate creative methods to solve twelve open-ended mathematical problems. Qualitative research design of case study was used in this study to explore the engineering undergraduates using creative methods to solve open-ended mathematical problems during creative problem solving processes. By analysing the data collected from the case study can provide in-depth and detail understanding of the creative processes and products of the research. Observation and recording sheets were used to collect all the data. SCAMPER was also used as a guideline for them to spark their creativity. All the qualitative data of drawing from documents, videotape from observation and snapshot texts from recording sheets were collected and then analysed. They were coded and categorized into different themes in order to find out the mathematical creativity among the engineering undergraduates. The results in this study shows that the engineering undergraduates were able to generate different creative methods with the help of the SCAMPER.*

Keywords: *Engineering Undergraduates, Creative Problem Solving, Convergent and Divergent Thinking.*

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I. INTRODUCTION

Engineers have to be innovative and creative in their professions. Engineers also need to have analytic skills as well as creativity to apply their knowledge and skills in solving problems in complex situations. They may have to use their creativity and analytic skills in order to apply and interpret the results obtained (Lee, 2006; Nichols & Weldon, 1997). The authors also pointed out that creativity can help engineers to think out of the box to find out unique and practical way to solve their problems (Lee, 2006; Nichols & Weldon, 1997). Problem solving is the heart of engineering and meanwhile mathematics is a critical tool in engineering. Mathematics can be creative and used as a scaffolding to foster their creativity. Engineering undergraduates can actually develop their mathematical creativity by solving an open-ended mathematical problem. Mathematical creativity is very important to engineering undergraduates to help them to come out with creative methods to solve their problems in the real world and it can be determined during the CPS. CPS works well for engineering undergraduates as they have to use both of their divergent and convergent thinking in all the stages of creative problem solving to solve the problem. The whole-brain approach of creative problem solving process can ensure that the engineering undergraduates have to switch on and off their both types of thinking.

According to Laycock (1970) mathematical creativity is the ability to look at the mathematical problems from different perspectives and generate many ideas and then select the best method to deal with them in different situations. Mathematical creativity can actually be developed with the use of creative problem solving skills. In the process of creative problem solving, engineering undergraduates have to use their divergent thinking to generate as many ideas as possible and then use their convergent thinking to select the best solution for the problem. The integration of creative problem solving with open-ended mathematical problem can help the engineering students to be more innovative and to get optimum solution in their problem-solving process. Open-ended mathematical problems can then be introduced in the engineering curriculum to stimulate the mathematical creativity of the engineering undergraduates.

There is a need for a framework for fostering mathematical creativity to help the engineering undergraduates in solving open-ended mathematical problem. Engineering undergraduates can use it as a guideline to solve open-ended mathematical problems. They can follow all the stages of creative problem solving to develop their mathematical creativity. To solve the problem creatively, engineering undergraduates have to go through the stage of problem definition, idea generation, idea evaluation, idea judgment and solution implementation. They also have to use both of their divergent and convergent thinking in all the stages of creative problem solving.

From the findings of literature review, it shows that two themes of mathematical creativity involved in the process of creative problem solving. The first theme is creative process which is known as the creative problem solving processes. Both divergent and convergent thinking were required in all the stages of creative problem solving starts from the first stage of problem definition, second stage of idea generation, third stage of idea evaluation, fourth stage of idea judgment until final stage of solution implementation. Second theme is the creative products of mathematical creativity and it can be developed from the creative processes of creative problem solving.

II. MATHEMATICAL CREATIVITY

Mathematical creativity is the ability of the engineering undergraduates to generate their creative ideas to solve the open-ended mathematical problems with the use of creative problem solving skills. Mathematical creativity required both divergent and convergent thinking in the process of creative problem solving. It is based on the use of divergent thinking in the processes of creative problem solving to generate many creative ideas. It is then filtered out by using convergent thinking to come out with the best creative method to solve the open-ended mathematical problems.

Runco (1993) also once said that: "*mathematical creativity is multifaceted and requires divergent and convergent thinking, problem finding and problem solving, self-expression, intrinsic motivation, a questioning attitude, and self-confidence*." According to Runco (1993), students have to explore themselves in using both of the divergent thinking and problem solving to develop their skills in fostering their mathematical creativity; creative problem solving is known as one of these skills.

Torrance (1987) applied the concepts of fluency, flexibility and originality to creativity in mathematics. He defined fluency as the ability to produce a large number of ideas, flexibility as the ability to produce a variety of ideas and originality as the ability to produce unusual ideas and elaboration as the ability to develop idea. Hadamard (1945) identified the ability to solve mathematical problems as the indicators of mathematical creativity. Kattou and others (2012) conducted a research on three hundred and fifty-nine elementary school students in Cyprus and they found out that the students' mathematical ability such as inductive and deductive problem reasoning ability can be used to predict their mathematical creativity. Bahar and Maker (2011) also conducted a research on seventy-eight second to fourth grade students in United States to explore the relationship between mathematical achievement and mathematical creativity and they found out there was significant relationship between them.

Henri Poincaré (1948) defined mathematical creativity as forming, recognizing and choosing important and useful combinations of ideas. He stated that there are four stages in creativity. The first stage is the preliminary stage of working hard consciously to come out with a solution to a problem. This is known as preparatory stage. The next stage is incubatory stage. At this stage, the problem is put aside for some time and then work with other problems. The third stage is the illumination stage, the solution suddenly comes out when the mind is occupied with other problems or engaged in other activities. The final stage is the verification stage. This is the stage to verify the result with words and to look for other uses of the result. The four steps of the Gestalt model is based on the conscious and unconscious work.

Sriraman (2005) considered mathematical creativity as one of the characteristics of advanced mathematical thinking. Ervynck (1991) connected mathematical creativity with advanced mathematical thinking and found out the relationships among them. Ervynck (1991) also considered mathematical creativity to create new mathematical concepts by combining previous concepts or discovering new and unknown relationships between mathematical facts. Solving old mathematical problems with different new methods can be considered as mathematical creativity. There are three different levels to solve real-life world problems. The first two levels can only come out with usual solutions; however, the last higher level can generate unusual and novel ideas based on mathematical creativity. Furthermore, he showed that there are three stages to develop mathematical creativity. The first stage is known as preliminary technical stage that just simply apply practical procedures or rules without any mathematical supports from any one. It is just to use mathematical techniques with no knowledge of theory behind it. The second stage is algorithm activity stage. At this stage, the mathematical procedures or algorithms are used to perform the mathematical techniques. The final stage is creative activity with decision making. The decision is based on the mathematical concepts. At this stage, true mathematical creativity can occur during non-algorithmic decision making.

According to Chamberlin and Moon (2005), mathematical creativity is based on divergent thinking to generate non-standard solution for a problem which can be solved by using standard procedures. Laycock (1970) claimed that mathematical creativity is the ability to look at the mathematical problems from different perspectives and generate many ideas and then select the best method to deal with them in different situations. Balka (1974) outlined six criteria to describe mathematical creativity. They are also used to check mathematical ability. The first is the ability to formulate hypothesis and the second is the ability to determine mathematical patterns. The third is the ability to break away from the stereotype mind setting and the fourth is the ability to evaluate unusual mathematical ideas. The fifth is the ability to sense the missing part of a problem and the last is the ability to split general problems into specific sub problems.

Idris (2006) pointed out that creativity-enriched mathematical problems rather than routine problems can be used to assess mathematical creativity. She also told us that this type of problems allow students to use different approaches to come out with many different possible answers. Torrance (1987) claimed that the tasks with the use of generating many possible solutions can be used to stimulate mathematical creativity compared to the tasks that can only generate one solution.

Hutcheson (1990) told us that two ancient mathematical problems can be used to stimulate mathematical creativity. The first problem is to trisect an angle into three equal parts and the second problem is to divide a circle into any number of equal parts. Craft (2001) pointed out that problem which can be used to generate more than one conjecture can be used to develop mathematical creativity.

Tanner and Jones (2013) suggested that practical tasks and real-life mathematical problems which are based on the procedure rather than the product can be used to help students to foster their mathematical creativity. Instruments used to assess mathematical creativity and creative problem solving on mathematics can be developed based on the definition of mathematical creativity as to determine the parameters of fluency, flexibility and originality (Torrance, 1974).

Evans (1964) found three parameters used to assess mathematical creativity such as fluency, flexibility and originality. Fluency is determined by the number of relevant responses generated, flexibility is the number of relevant responses in different categories of ideas generated and originality is the number of unusual ideas generated.

SCAMPER is used as the guideline in this research to help the engineering undergraduates to generate their creative ideas to come out with creative methods to solve the problem. They applied SCAMPER in the stage of idea generation to come out with multiple ideas. SCAMPER stands for Substitute, Combine, Modify (Magnify, Minify), Adapt, Put to other uses, Eliminate and Rearrange (Reverse) (Serrat, 2017).

III. METHODOLOGY

Research Design

Case study

A case study is used in this research as it can be considered as a practical and useful tool in the research of small sample size. It can also provide a better insight and more detail understanding of the situation in the real-life context. By using the qualitative data from the case study, it can be used to provide in-depth explanation of the process and outcome of a study (Zainal, 2007; Tellis, 1997), Zainal (2007) pointed out that the qualitative data from the case study can also be used to explore and provide very good description in the complex real-life situation which can't be obtained with the use of other research method. A qualitative research design is used in this study as it only collect all the qualitative data of videotaping from observation, texts from recording sheets, drawing and pictures from documents.

Participants of the study

Three final year (fourth year) electrical engineering students participated in the study, namely: Chin (24 years old), Ng (24 years old) and Goh (23 years old). These were not their real names. They were classmates and therefore they were comfortable with each other in the group discussion. All the three students had not taken part in any CPS training before. They claimed that they would like to solve creative mathematical problems, take part in the projects that involved creativity, apply mathematics to solve the real world problems and work in a group. All of them except Chin would like to design something.

Data Collection Instruments

There are three qualitative data collection instruments used in this research such as documents, observation and recording sheets. Observation transcripts are the data collected from videotaping during the observation, documents are the drawing and the writings of the engineering undergraduates collected during the observation and recording sheets are the written records collected from the engineering undergraduates. The interactions as well as their drawing processes are videotaped in the process of problem solving. Their conversations and dialogue are also recorded in the video and then transcribed. Open-ended mathematical problems are used to study the engineering undergraduates how to use their creative methods to generate their ideas and solutions. The recording sheets of the engineering undergraduates are then collected as documents for document analysis. Students' drawing and observation transcripts are also used to find out the mathematical creativity of engineering undergraduates to solve open-ended mathematical problems.

Data Triangulation

All the three different data collection methods are also used to help to triangulate the data. The qualitative data would also be analysed from the recording sheets, observations and documents. These are thick and rich descriptions of personal perceptions and point of views which are very useful in understanding engineering undergraduates solving the problems creatively and critically. All these qualitative data are then combined at the end of data collection to verify the results by means of triangulation in order to study the use of creative problem solving in mathematics. With the help of these different methods, it can provide a richer and more authentic description of the fields to investigate. In order to find out how the engineering undergraduates are going to use creative problem solving in their mathematical problem-solving and to understand the engineering undergraduates' interactions and discussions, using triangulation in data collection can provide significant insight into their discussions while they are engaged in solving open-ended mathematical problems and building of knowledge through mathematical thinking. Therefore, at the end of data collection, it can get deeper understanding of their thinking skills in using creative problem solving on mathematics. All the qualitative data will be collected and therefore can help to uncover and to understand the findings. Three final years engineering undergraduates took part in the study and they were named anonymously.

IV. FINDINGS

One of the problems required students to come out with many designs of an electrical can crusher to crush all the cans in a recycle centre to increase the space of storage. Students had to explain their designs and also provide the detail dimensions of the machine and its electrical components. They had to use both of their divergent and convergent thinking to generate many design to solve the problem.

Student Ng started to tell us his design. He said that there are four processes in his machine namely sorting, preparation for crushing and crushing, and then the finally is channeling to the bag. His design consists of at a big funnel at the top of the machine, so that all the cans can be poured into the funnel, it allows ten rows of the cans to be poured into bins. The close gate which is automated by vision trapper will open and once the cans fall through it, the close gate will close the gate, the hydraulic and pneumatic piston which are supported by a base and powered by motor will crush the cans. After crushing it, then the cans will slip into the bags. His machine with a forty five degree offset from the base can allow the cans to fall into the bag. Figure 1 shows that student Ng used a machine to crush a lot of cans at one time. From the observation transcript:

"*okay, my design keke... basically err..ya... four processes, got sorting, got err... preparation for crushing and crushing, and then the finally is channeling and then, to the bag, so my design will be at the err.. a con.. a big funnel*."

(C36 day10(c)transcript)

"*a big funnel right, at the top, so all the cans will pour into here, and then, for err.. and then have ten rows, ten rows for the size of the cans into bins to and then, here got the, got err.. what we call the, err.. close gate, the close gate will be automated by vision trapper and then after the can err.. the close, the close gate open, and then, the can fall into here, and then, the close gate close the gate, and then, and the motor here is the piston, so the piston will have hydraulic and pneumatic pistons support, any support from the base and then, it will crush the cans, okay, if after it crush it, then the cans will slip into the bags, so the design will be like a machine that it has forty five degree off, off the, from the base, because it will allow the cans to, to fall to the bag*."

(C38 day10(c)transcript)

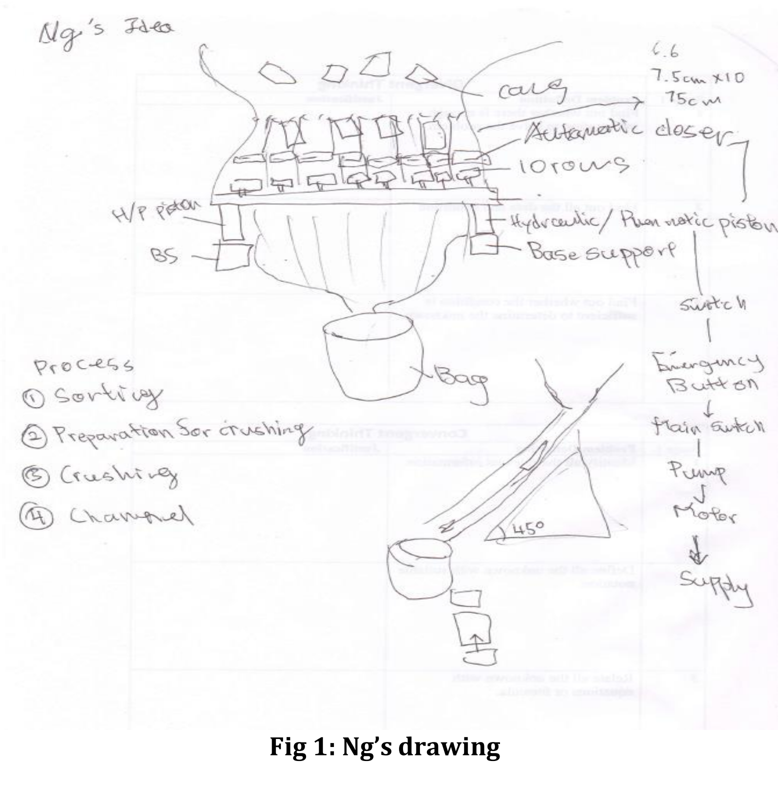


Fig 1: Ng's drawing

For student Ng, he used the method of substitute in SCAMPER. He substituted one part for another to create something different, so he substituted the piston and the automatic closer in his design to come out with something different in the process. He also used the method of combine to combine different types of technology together to form a complete system. From the observation transcript:

"*me, okay, for the method I use, I use substitute which I substitute one part for another to create something different, so I substitute err.. the piston, the automatic closer together to form something different in the process.*"

(C68 day10(d)transcript)

"*so, and then, the another method I use is combine, which I combine err... different types of technology together to form a complete system,..*"

(C70 day10(d)transcript)

The triangulation of data in Figure 2 shows that Student Ng came out with an automation design which can crush a lot of cans at one time without any manual labour. The data was collected from his drawing, observation transcript and snap shots of text.

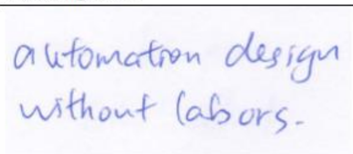
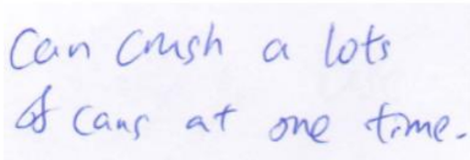
Evidence from Document	Transcripts from Observation	Snap shots from idea evaluation form (Ng) Recording Sheets
The drawing shows that it is a simple automated design that can save time as it can crush a lot of cans at one time.	*....m... automation design without manual labor.* [C131day10(d)]	
	can crush a lot of cans at one time. [C129day10(d)]	

Fig 2: Triangulation of data (Ng)

For student Goh, he came out with the design of a machine attached to a box which can allow the cans to be stacked up. Once the can falls into the box, the roller will turn and there is a piston to crush the can. The piston will move forward and backward. The crushed cans will then slip to the space as below and drop into bottom of the machine. He continues to mention his second design. There is a roller and sensor in the machine. Once the box is over-packed with cans, then the channel will close and the heavy piston will crush the can. Once the piston lift up and the roller will continue to roll and the next can actually fall into the bins. His design is shown in Figure 3. From the observation transcript:

"*err..err... m... for me, with a, is like a straight box, you have to put one by one inside, then, you stack up, okay, so, the, every time, when one fall down here, the, there will be a something like a roller.*"

(C42 day10(c)transcript)

"*and will turn and there is a piston will err.. will, like a piston have to crush the can first, then only can make, like a go fro and back, fro and back right, ya... so, once the, the, the tin already crush, the can lah... and then, it will be small right, then, it will slip to the, the space and below, err... below here, and drop into bottom lah...* "

(C44 day10(c)transcript)

"*ya.. this is the first design, second one is actually apply roller as well, we just put it, when it actually go into here, there will be sensor, like is err.. like really maximum already, the channel, will close and then, the, the, the heavy piston will crush the can, and lift up again and then, the roller will continue, and the other will actually fall into the bins or something lah... m.. this is my design lah.. ya…*"

(C46 day10(c)transcript)

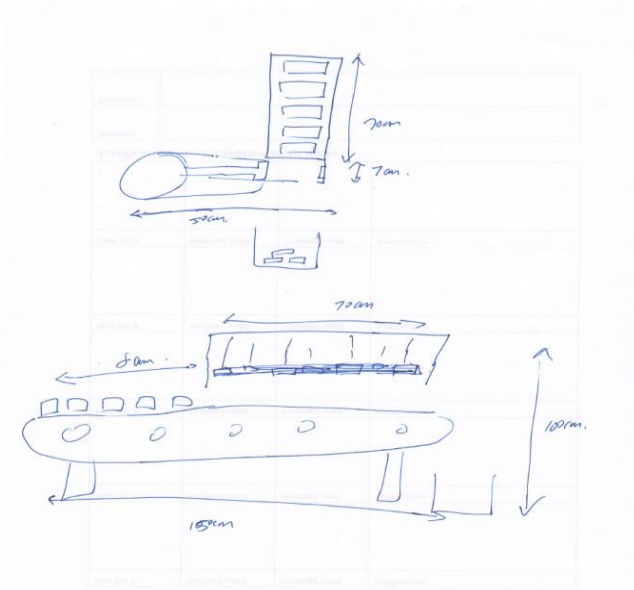


Fig 3: Goh's drawing

Student Goh used the methods of combine and adapt. He combined other ideas or part of other ideas to create something new. He got all sorts of ideas from Google search and then he modified them to come out with his new idea. He also adjusted other idea to help him to solve the problem. From the observation transcript:

"*okay, so, err.. for me, I am using combine and adapt lah... then, I combine other ideas or parts to create something new to help me solve the problem, so, I go all sorts for ideas through Google and I modify it, ya… make it something new, and I adjust something to help me solving the problem as well, ya...* "

(C73day10(d)transcript)

"*..adjusting the other idea lah…*"

(C75 day10(d)transcript)

The triangulation of data from document, observation and idea evaluation form in Figure 4 shows that student Goh's machine is simple in design and not well-designed.

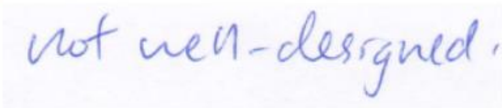
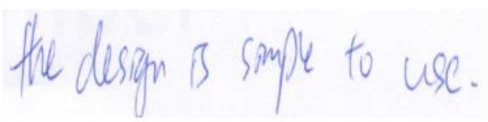
Evidence from Document	Transcripts from Observation	Snap shots from idea evaluation form (Goh) Recording Sheets
The drawing shows that it is a simple design and easy to be used.	*m… is not really that err.. well design, he.. because it is a very simple one, ya…* [C143day10(d)]	
	…err.. as the design is err… quite simple and easy to use err.. [C139day10(d)]	

Fig 4: Triangulation of data (Goh)

After that, Student Chin describes his design. He says he comes out with a design of a machine with a conveyor and there is also a sensor which can detect the number of cans. Once, it allow certain amount of cans, it will crush the cans at once. The crushed cans will roll into the collector bin. His drawing is shown in Figure 5. From the observation transcript:

"*so, when, the tins, is a conveyor lah... and they can, when it detects the number of cans, then, it can crush*."

(C54 day10(c)transcript)

"*then, the crush will be roll into the collector*."

(C56 day10(c)transcript)

"*so, m... my thinking about how last time industry, it operate, I think they, how they operate the machine, so they use something like conveyor move all the products, so we adapt this into this problem and the second thing is we arrange, can recognize the components to help me solve the problem*."

(C60 day10(d)transcript)

Student Chin mentioned his creative methods used in the problem. He told us that he used the method of adapt. He used the conveyor to move the cans as he adapted the methods used in the industry. He also recognized the components of the machine and then arranged them in his design. From the observation transcript:

"*okay, so, I start with mine, idea number one, Chin's, so the method I use, SCAMPER right*."
(C56 day10(d)transcript)

"*is adapt*."
(C58 day10(d)transcript)

"*so, m... my thinking about how last time industry, it operate, I think they, how they operate the machine, so they use something like conveyor move all the products, so we adapt this into this problem and the second thing is we arrange, can recognize the components to help me solve the problem*."
(C60 day10(d)transcript)

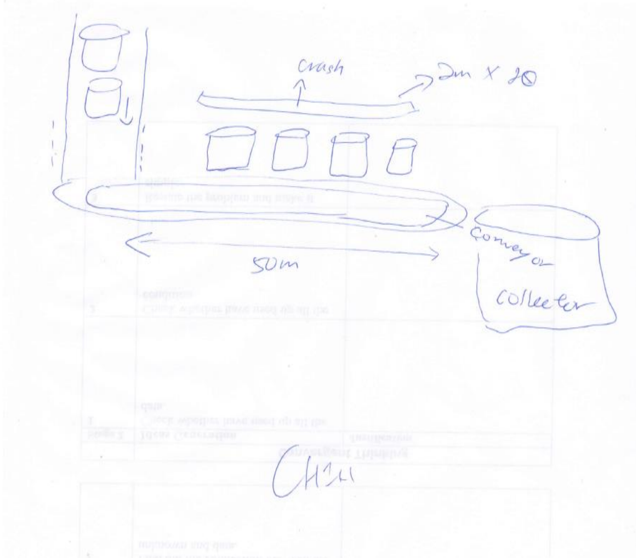


Fig 5: Chin's drawing

Figure 6 shows the triangulation of data collected from three different sources; student Chin's drawing from the document, observation transcript and snap shots of text of idea evaluation from recording sheet. He convinced others that his design of conveyor can help his machine to crush large amount of cans continuously.

Evidence from Document	Transcripts from Observation	Snap shots from idea evaluation form (Chin) Recording Sheets
The drawing shows that it is a design of a machine with a conveyor that can crush large amount of cans continuously.	*..conveyor keep moving…* [C123day10(d)]	converyor keep rolling and save time.
	…..it can crush large amount continuously…. [C125day10(d)]	Can crush large amount continuosly.

Fig 6: Triangulation of data (Chin)

The following table shows the mathematical creativity of the students fostered after the creative problem solving processes. It was evaluated based on the parameters of fluency, flexibility and originality. Torrance (1974) claimed that parameters of fluency, flexibility and originality can be used to assess mathematical creativity. Evans (1964) also stated that mathematical creativity can be asssessed based on the parameters of fluency, flexibility and originality. Keh and others (2017) came out with an assessment method to find out the creativity among the engineering undergraduates based on the paramters of fluency, flexibility and originality. Fluency is determined by the amount of solutions, flexibility is the different categories of solutions and originality is the unique solution given by the students. The results in this problem is shown in Table 1. It shows that the engineering undergraduates came out with three solutions, one type of solution and one original solution.

Table 1: Mathematical creativity fostered in the problem

Fluency	Flexibility	Originality
Three different solutions Chin's solution: (1) He designed a machine with a conveyor that can crush large amount of cans continuously. Goh's solution: (2) He came out with the design of only a simple machine to crush the cans. Ng's solution: (3) He came out with a simple automated design that can save time as it can crush a lot of cans at one time.	One type of solution They used drawing to help them to visualize the problem	One unique solution They combined all their ideas and came out with a high reliability engineering design. C114 day11(a)

Table 2. Mathematical creativity fostered in the twelve problems

Problem	Fluency	Flexibility	Originality
Problem 1	3	2	1
Problem 2	3	3	1
Problem 3	3	2	1
Problem 4	4	2	1
Problem 5	3	2	1
Problem 6	3	2	1
Problem 7	3	2	1
Problem 8	3	1	1
Problem 9	3	2	1
Problem 10	3	2	1
Problem 11	3	2	1
Problem 12	3	2	1

Table 2 shows the mathematical creativity fostered in the twelve problems. Fluency is the ability of engineering undergraduates to generate different solutions to solve the problem. Flexibility is the ability for them to come out with many different types of solutions and originality is the ability to come out with unique solution to the problem. It shows that problem number one, two, four and nine can be used to generate more solutions. The data was obtained from their drawing and sketches. It was triangulated with observation transcript and snapshot of texts from idea evaluation form.

In this research, it shows that engineering undergraduates list out all the creative methods to solve the problems by using divergent thinking and then select the best methods by using the convergent thinking. Thus, they learn to use their creative problem solving skills to solve open-ended mathematical problems throughout the study. The students learn that they have to consider other factors before solving the problem. They have to meet not only the requirements in solving the open-ended mathematical problems, but also to fulfil most of the criteria in the problem. In the problem of designing a car park, they have to maximize the number of parking space as well as to find out whether it is time saving, efficient and practical for the drivers to find the parking space.

V. CONCLUSIONS

The results of the research shows that creative problem solving can be applied in solving open-ended mathematical problems. This research also shows that engineering undergraduates have to use different creative methods to solve open-ended mathematical problems.

Open-ended mathematical problems in this research are not well-defined and therefore engineering undergraduates cannot use fixed procedure to solve the problems. They have to use their divergent thinking to come out with different approaches to solve the problems based on their creativity and imagination. Students are given good opportunity and freedom to use their creative thinking to generate their ideas. They can also learn how to gather enough information to solve the problem with the use of creative problem solving skills.

It also shows that engineering undergraduates interact and work collaboratively in the process of creative problem solving to come out with different creative methods by using brainstorming. They interacted with their teammates and constructed new ideas in solving the open-ended mathematical problems. They even modified and combined their ideas with others to come out with something new. They also developed new understanding of the problem with the help of their teammates. Therefore, they can modify ideas by considering others' views and opinions and finally came out with their own new ideas after interacted with each other during brainstorming. This shows that engineering undergraduates can learn to generate many possible creative methods to solve the problems by using brainstorming in an activity of small group discussion.

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