Formulating An Engineering Design Problem: A Structured Approach

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Abstract: During recent times, several initiatives have been taken to redesign engineering curriculum to introduce students to the engineering design process starting from the freshman year itself. This involves taking these students from a world of exercise problem solving having single unique solution to the world of real wide engineering problem solving having multiple solutions. And it is observed to be a challenging task as the students are not familiar with ill-defined nature of engineering problems and are having a tendency to get stuck with the first solution that they get. Problem formulation is the first step in engineering design process in which students are expected to carve out problem definition for a given need statement. Students face difficulties in this step, in framing the problem statement and representing it in terms of functions, objectives and constraints depicting an engineering system.In this work, authors share their experience of mentoring freshman students in problem formulation phase of their course project which is done as part of a course, titled, "Engineering Exploration". The work is presented in terms of its evolution of the pedagogies and practices over three cycles of the delivery of the course. An inclusive pedagogy consisting of in-class, case-based reasoning and template based structured mentoring has resulted in improved quality of formulated problems. The paper discusses the details of processes and pedagogy.

Keywords: Design thinking, need statement, problem statement, Design problem, Pair wise Comparison Chart (PCC)

1. Introduction

Engineering has been defined as an application of Mathematics and Natural Sciences to solve societal problems by designing technological solutions (ABET).

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The engineering solutions; which are outcomes of following the engineering design process; are thus a synthesis of technical knowledge, technological ingenuity and innovation (Sheppard, Macatangay, Colby & Sullivan, 2008). Engineering design has been defined as "a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints". Engineering Design is thus portrayed as a thoughtful process and is referred to as design thinking in which the professional explores the problem at hand to develop solutions beyond the obvious. It engages the user in convergent-divergent questioning, making evidence-based decisions among many other cognitive tasks (Dym, Agogino, Eris, Frey & Leifer, 2005).

The onus of teaching the engineering design process and the associated skills lies on the academicians who need to create effective experiences in design project work across the four years. The thrust towards creating engineering practise based learning also comes from external stakeholders like industries (Lang, Cruse, McVey, & McMasters, 1999) and is prescribed as the third graduate attribute of the Washington Accord (Washington Accord).
Many universities worldwide have initiated students into the design process starting as early as the freshman year itself.

The focus of this paper is on one such freshman course titled, "Engineering Exploration" whose outcomes are to expose the freshmen to the essential aspects of engineering profession namely Engineering Design, Multi-disciplinary nature of Engineering Problem Solving, Platform Based Development, Data Analysis and Acquisition and basics of Project Management, Sustainability and Engineering Ethics using a hands-on approach. As a part of this course, the students engage in a semester-long engineering design project given the need statements.

The scope of this paper lies in the module of Engineering Design which involves the five step design process: Problem definition, Concept generation and Selection, Preliminary Design, Detailed Design and Design documentation. During In the problem definition step the students are required to formulate the essential problem statement, establish objectives, define constraints and identify functions to make the proposed solution viable to stakeholders.

Formulating a problem statement is a challenging cognitive task due to many reasons; it requires the students to organise the problem in terms of objectives, constraints, functions and assumptions which are to be expressed in engineering requirements. To be able to do this, the students have to formulate and pose questions, sift through answers and information (Dym, Little, Orwin, & Spjut, 2009). Another issue which increases the complexity of the problem formulation step is that need statement is written in simple English sentences, whereas a problem statement is to be framed such that it manifests an engineering system. Therefore, how to interpret the simple English language statements with the intention of quantification is a problem.

To address these challenges, this paper outlines the processes and pedagogies adopted for the problem definition phase during three different cycles of freshman course, “Engineering Exploration” and analyses the effectiveness of each in helping students establish the problem statement from the given need statement. The remainder of this paper presents the survey of the literature, the methodology, results and discussion.

A. Background Literature

The scope of this literature review lies in understanding nature of Engineering design problems, the need and significance of Freshman Design courses, the pedagogies adopted to teach engineering design, challenges faced by faculty and students in teaching and learning engineering design and the strategies adopted thereof.

1) Engineering Design and Design Problem

Dym(2005) has stated that design thinking is a complex and a thoughtful process. For the sake of scoping, the author has defined Engineering design as a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients’ outcomes or users’ needs while satisfying a specified set of constraints.

Howard (1988) states that among the steps in the process of design, “the framing of design decision” is also considered to be most engaging and difficult to teach as it involves uncovering the exact problem to solve and prevents solving the wrong problem. This process of uncovering the exact problem involves asking right questions, the answers to which establish the systems functions, constraints and objectives. Questioning is clearly an integral part of design (Dym, Agogino, Eris, Frey & Leifer, 2005).

Additionally, design problems are “ill-defined”, “wicked”, “complex” (Stojcevski, 2014) and do not have a single correct solution; and so far in their schooling the freshman are prepared for a convergent mindset of thinking as against a divergent mindset needed to solve design problems. Crismond & Adams (2012) highlight the patterns exhibited by novice and informed designers in their work. The novices consider the design problem as well-defined problems and proceed to solve it immediately whereas the experts explore, deliberate and comprehend before frame the problem.

2) Freshman Design Courses

There are been tremendous interest in including design experience during the freshman year. Research has shown that Freshman Design courses, also referred to as cornerstone design projects (Dym, 1999), reduce attrition rate, increases persistence throughout engineering program and develop project based skills (Knight, Carlson & Sullivan, 2007). Additionally, they also provide positive learning experiences for faculty and students alike (Bransford, Brown,Cocking, 2000). Design experiences during the freshman year also develop professional skills like teamwork, communication, and time and project management. Since, such multi-week design courses generally parallel the other engineering and basic science courses, they allow for synthesis of knowledge gained. Such freshman design courses provide students an interactive, encouraging and a “fail-safe” environment in which the students learn to deal with ambiguous nature of engineering problems and develop an understanding of engineering profession. (Sheppard, Macatangay, Colby& Sullivan, 2008). The design courses concentrate mostly on the design process and thus provide freshman an opportunity to play the “junior of the whole game”.

3) *Pedagogy for Design teaching and Learning*

The dominant pedagogy to teach design skills and processes is Project Based learning (PBL). PBL is a “design-oriented project-organised education which deals with practical problems of constructing and designing on the basis of synthesis of knowledge from many disciplines and is therefore having students learn to know *how*"(Dym, 2005). At the heart of PBL lies the design problem, and by working through this design problem to develop a tangible solution, the students learn to apply the design process and skills. Among the other pedagogies, case-based reasoning, reverse engineering, role playing games complement PBL (Sheppard, Macatangay, Colby & Sullivan, 2008).

4) Challenges of introducing freshman to Engineering Design

Teaching Design to freshmen has its own set of challenges. The technical (maths and science) knowledge of the students is limited and their exposure to technological know-up is scarce. By keeping in mind this limited repertoire of students' skill set, formulating appropriate design problems is a serious and a thoughtful task. Additionally, to facilitate the seamless learning and application of the design steps, the faculty needs to compile resources which are tailored to suit the students' learning needs. (Sheppard, Macatangay, Colby & Sullivan, 2008).

Another challenge arises from the current cognitive ability of the students. The freshman students' cognitive development is not suited to the mode of enquiry and divergent mindset which the process of design requires. Design thinking requires a reflective thinking. At the age, at which students enter undergraduate courses, they are either in pre-reflective or quasi-reflective thinking phase of development. They are not developmentally ready to handle ill-defined nature and ambiguous contexts of engineering problems. Thus the faculty needs to create learning resources and pedagogies which stimulate and promote reflective thinking (Felder & Brent, 2004).

Table 1 Themes for 2015-2016(fall)

Division	Theme
A	Solar Energy Utilization
B	Wind Energy Utilization
C	Waste Management Solutions
D	Water Management Solutions
E	Agri Mechanization
F	Pollution Control
G	Waste Energy Harvesting

B. Proposed Work

The mandatory course, "Engineering Exploration" introduces the freshman to the engineering design process using hands-on activities. The pedagogy followed is Project based learning (PBL). The students engage in a semester long course project for which the need statements are given. The students follow the five-step Engineering Design process to design prototypes or proof of concepts.

In this work, the authors have only addressed the challenges of mentoring the students in the first step of Engineering Design process; formulation of problem statement. Formulation of the problem statement is a challenging task as the students cognitive development is not yet mature enough to understand ill-defined engineering problems. The students face difficulties in structuring the given need statements in terms of objectives, constraints and functions, quantify and represent them in engineering terms.

This work tracks the processes and pedagogies followed during three cycles 2015-2016 (fall), 2016-17 (spring) and 2017-2018 (fall) in the freshman course Engineering Exploration in mentoring the students during the problem formulation phase of their course projects

C. Research Question

1. How does process and pedagogy influence the outcomes of the problem formulation phase of the Engineering Design process?

D. Research Hypothesis

1. The process of structured mentoring using templates and case-based reasoning positively helps students in formulating the problem statement from the given need statements in terms of defining objectives, functions and constraints.

2. Methodology

In light of the stated proposed work, research questions and research hypotheses, the authors intend to describe the process and pedagogy adopted to mentor the freshmen during the problem formulation phase of the course projects during the three different cycles 2015-2016 (spring), 2016-17 (fall) and 2017-2018 (spring). The progression in the process and pedagogy across the three cycles is shown in figure 1.

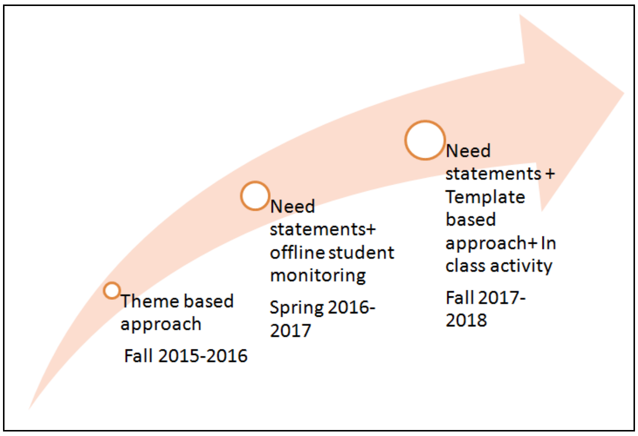

Fig 1 The progression across cycles

During all three cycles under study, the freshmen were segregated into divisions each having 64 students. For the course project, the students worked in teams of four students each and were mentored by a faculty who served as a guide. The team submitted a prototype/proof of concept at the end of the semester.

The subsequent sub-sections outline the process and pedagogy followed during the three aforementioned cycles

A. Process and pedagogy followed during 2015-2016 (fall)

During this semester the course Engineering Exploration was delivered to the students for the first time. For the course projects, a theme based strategy was followed and seven themes were floated across the divisions. The themes were chosen with an intention of orienting the freshmen towards grand engineering challenges (Atkins, 2013). Each division was assigned a theme. The students were required to identify of needs under given themes. After identification of the problem, the steps that were followed to guide students to formulate the problem statement are as follows:-

i. Identification of problem.
ii. Perform need analysis
iii. Formulation of problem statement.

As an example case, a verbose case study was given to students in the form of a guiding document which contained a need statement and the formulated problem statement. The students were expected them to learn from the example and formulate the problem statement by applying their understanding to their identified problem.

The case study which served as a guide is outlined below.
Need:"Design a better mousetrap."
Problem statement: "A Better Mousetrap: Certain rodents such as the common mouse are carriers and transmitters of an often fatal virus, the Hantavirus. Conventional mousetraps expose people to this virus as they handle the trap and dispose of the mouse. Design a mousetrap that allows a person to trap and dispose of a mouse without being exposed to any bacterial or viral agents being carried on the mouse."

A Problem statement formulated by the student team under the theme Wind Energy Utilisation is shown below.

Title of the project: Wind Powered Aqualator
In agriculture fields, farmers find it difficult to lift water from the water source with use of electricity, as there is shortage of electricity. Wind powered aqualator helps to lift water without using electricity i.e. by converting wind energy directly to mechanical energy

The students were required to submit their problem statement at the end of 15 days. However, no structured or uniform mentoring was followed.

B. Process and Pedagogy followed during 2016-2017 (spring)
During this semester, twelve need statements were floated across the eight freshman divisions. The intention of the need statements was to orient students towards developing smart systems that includes sensing, controlling and actuation. The students chose the need statements based on their interest.

To help during the problem formulation phase, the same verbose case study of the "mouse trap design" was given to students in the form of a guiding document. Similar to the previous semester, no structured and uniform mentoring was followed. But based on the learnings' from the previous semester, the faculty followed personalised approaches to mentoring during this phase. This led to varying degrees of quality in the problem statement.

A sample need statement assigned to a student team
Ex. In a juice centre, the outlet has planned to introduce mock tails. But, it has been observed that pre-mixing juices to prepare mock tails cannot be achieved as the resulting liquid loses its taste on storage. Also, there is a shortage of staff to serve at the outlet throughout the day. Hence, provide a solution which dispenses the liquid as per the quantities in the defined recipe and stirs the liquid to ensure consistency. Dispense the liquid in a glass which will be picked up the customer.

A sample problem Statement 1 formulated by the student team
The demand for mock tail has been growing rapidly over the past few decades and so is the need of an automated mock tail maker. "The Moc-maker" makes mock tail making easy and less time consuming. It uses the simple mechanism of gears and mixes using pressure, it also has an easy cleaning method which ensures that there is no spillage of juices. Keeping affordability in mind, The Moc-maker costs less than Rs. 3000.

C. Process and pedagogy followed during 2017-2018 (fall)
During this semester, twenty seven need statements were floated across seven divisions of freshman students to orient students towards developing assembly line systems that includes sensing, controlling and actuations. A sample need statements is shown below:-

A factory in Hubballi is keen in setting up an automatic packaging assembly line. Below are their requirements.

1. A robot which picks and places the packaging box of size 20cm x 15cm x15cm on the conveyor.
2. A robot which picks and places a product of size 15cm x 10cm x 10cm into the packaging box of size 20cm x 15cm x 15cm which is moving on a conveyor.
3. A robot which folds the top flaps of the packaging box of size 20cm x15cm x 15cm which is moving on a conveyor.
4. A robot which applies duct tape on the packaging box of size 20cm x15cm x 15cm which is moving on a conveyor.
5. A robot which applies label and stamps the package box which is moving on a conveyor.

6. A robot which picks the packaged boxes of size 20cm x 15cm x 15cm which are moving on a conveyor to another place.

To help the students formulate the problems statements learning resources and templates were compiled. The steps followed to help freshmen arrive at problem statement included:-

i. Describing the entire design process in a class room environment.
ii. Demonstrating the process of translating the need statement into problem statement through a case study which consisted of
    a. Identification of stakeholders
    b. Preparation of questionnaire to understand stakeholder requirements in an effective way.
    c. Segregating the answers from stakeholders into objectives, constraints and functions.
    d. Prioritizing the objectives using pair wise comparison chart
    e. Defining sub functions of a function
    f. Formulation of problem statement that clearly reflected objectives, constraints and functions.

At the end of 5 days, the students were required to submit the problem statements by following the template given in the appendix. The soft copy of the template was shared with the students.

A Sample Problem Statement

Design a pick and place robot which can pick and place packed boxes of dimensions 20cm X 15cm X 15cm which are moving on a conveyor belt. The robot must be portable. Robot should be able to lift boxes of different dimensions other than a specific size only. The robot must have modularity. The robot must be reprogrammable for further usage. Robot must be safe to handle and simple to use. The robot must be able to lift the weight of at least 500 grams. The cost of the robot must not exceed beyond 3500 rupees. The robot must be able to count the number of boxes being lifted. The robot must be able to pick /lift the box and be able to carry it to other place and drop/place it.

3. Results

From the problem statements formulated during three semesters the following observations can be made. During 2015-2016(fall) the problem statements formulated by the students were completely open ended and lacked clear objectives, constraints and functions. During 2016-17 (spring), the formulated problem statements were also open-ended and lacked clear objectives, functions and constraints. However, the quality of the formulated problem statement depended on the guide.

During 2017-2018 (fall), the problem statements formulated from students were clear in terms of listing objectives, defining the boundary of the system and stating the functions. This clarity in problem statement helped the students to write better transparent model and eventually better conceptual design.

4. Discussion

It has been highlighted earlier in the literature survey that formulating the problem statement is a challenging task as it requires the students to organise the problem in terms of objectives, constraints, functions and assumptions which depicts the engineering system to be designed. To be able to do so, the students have to formulate and pose questions, sift through answers and information (Dym, Little, Orwin, & Spjut, 2009). This process of uncovering the exact problem involves asking right questions, the answers to which establish the systems functions, constraints and objectives. Thus, questioning is clearly an integral part of design (Dym, Agogino, Eris, Frey & Leifer, 2005).

In the third approach of mentoring the students during the problem formulation phase of their course projects, the authors have followed the pedagogy of in-class, case-based reasoning and template based structured mentoring.

The templates shown in the Appendix require the students to pose questions regarding the system to be designed. The students act both as stakeholders and the designers in understanding the system. Such a uniform approach has shown promising results as is evident from the problem statements formulated during 2017-2018 (spring).

Thus, as per the research hypothesis, the process of structured mentoring using templates and case-based reasoning helps students in formulating the problem statement from the given need statements in terms of defining objectives , functions and constraints.

5. Conclusion

The course, "Engineering Design" aims at initiating freshman into Engineering Design process. Our experience of four cycles in mentoring the freshman in the course project has been a eventful learning experience by experimenting with different processes and pedagogies in teaching engineering design. From our latest experience in 2017-2018 (fall), the pedagogy of in-class, case-based reasoning and template based structured mentoring during the problem formulation phase has shown positive results. However, problem formulation is just the first step of the five-step engineering design process which the freshman follow in this course. The authors hope to unearth the challenges present in the subsequent design steps and devise effective processes and pedagogies to help students seamlessly learn and apply the process.

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References

Atkins, R. (2013). Grand Challenges for Engineering. Chicago

Bordogna, J., Fromm, E., & Ernst, E. W. (1993). Engineering education: Innovation through integration. Journal of Engineering Education, 82(1), 3-8.

Bransford, John D., Ann L. Brown, and Rodney R. Cocking. "2000." How people learn: Brain, mind, experience, and school.

Crismond, D. P., & Adams, R. S. (2012). The informed design teaching and learning matrix. Journal of Engineering Education, 101(4), 738-797.

Dorst, K. (2011). The core of 'design thinking' and its application. Design studies, 32(6), 521-532.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., & Leifer, L. J. (2005). Engineering design thinking, teaching, and learning. Journal of Engineering Education, 94(1), 103-120.

Dym, C. L., Little, P., Orwin, E. J., & Spjut, E. (2009). Engineering design: A project-based introduction. John Wiley and sons.

Dym, C.L., "Learning Engineering: Design, Languages, and Experiences," Journal of Engineering Education, Vol. 88, No. 2, 1999, pp. 145–148.

Felder, R. M., & Brent, R. (2004). The intellectual development of science and engineering students. Part 1: Models and challenges. Journal of Engineering Education, 93(4), 269-277.

Howard, R.A., "Decision Analysis: Practice and Promise," Management Science, Vol. 34, No. 6, 1988, pp. 679–695.

Knight, D. W., Carlson, L. E., & Sullivan, J. F. (2007, June). Improving engineering student retention through hands-on, team based, first-year design projects. In Proceedings of the International Conference on Research in Engineering Education. Honolulu, HI.

Lang, J. D., Cruse, S., McVey, F. D., & McMasters, J. (1999). Industry expectations of new engineers: A survey to assist curriculum designers. Journal of Engineering Education, 88(1), 43-51.

Rodgers, P. (2013). Articulating design thinking. Design Studies, 34(4), 433-437.

Sheppard, S. D., Macatangay, K., Colby, A., & Sullivan, W. M. (2008). Educating engineers: Designing for the future of the field (Vol. 2). Jossey-Bass.

Stojcevski, A. (2014). Learning to solve 'design problems' in engineering education.

Washington Accord http://www.ieagreements.org/assets/Uploads/Documents/History/25YearsWashingtonAccord-A5booklet-FINAL.pdf