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Developing Creative and Critical Thinking Skills Through Open Ended Design Projects at the Freshman and Senior Level

John Tharakan
Department of Chemical Engineering, Howard Universty, Washington DC, USA
jtharakan@howard.edu

Abstract: It is crucial that engineering students develop creative and critical thinking skills as part of the skill set needed to become real world problem solvers. Incorporating exercises that encourage and develop creative and critical thinking skills in students is essential for a syllabus to achieve outcomes that demonstrate adequate preparation of the student of engineering to face real world challenges. In this paper, we report on the inclusion of open ended design (OED) type projects that students work on in teams as part of the requirements for both a freshman level introduction to chemical engineering design course and for a senior level core chemical engineering course or kinetics and reactor design. The paper outlines the key components of such exercises and articulates on the specifics of how these are assigned to students, the process by which the students work in collaborative groups and teams to develop the open-ended solution and discourses on the rubric that students are provided so that they are aware of how the assessment and evaluation of their work will be conducted. The paper articulates on the components of the final report and presentations that the students teams are expected to develop and deliver. Finally, we discuss the student educational outcomes that are being appropriately addressed through such OED projects, and report on our experience in terms of the achievement of the highlighted outcomes by the students.

Keywords: Creative thinking, critical thinking, open-ended design, freshman level, senior level

1. Introduction

Engineering and engineering education has been evolving over the past century or more as technology and society have themselves evolved and developed. As a formal discipline, engineering education only began in the late 19th/early 20th century. There have been a series of policy reports that have been developed and produced by various learned, scholarly and professional societies over the years focused on engineering education content, curricula and pedagogy, and these demonstrate the changes that have occurred in the conceptualization of engineering education (Cheville, 2014).

The first rigorous policy paper on engineering education was the Mann Report (1918), which had been commissioned by three engineering societies through the Carnegie Foundation. The Mann Report took as it's premise that the purpose of engineering was to improve industrial production and also to elevate the mechanical arts to a learned profession. It saw the role of the engineer as that of a manager with the charge to apply scientific principles to industrial

John Tharakan
Department of Chemical Engineering, Howard Universty, Washington DC, USA
jtharakan@howard.edu

production. Preparation for an engineer included learning science, applying science in the mechanic arts, developing managerial skills and building character. Thus engineering education programs were to balance scientific, technical, and humanistic studies to produce graduates with a measure of knowledge and character who could be active in their roles in industry; the focus was highly pragmatic. Although taught in universities, engineering was not to be a purely academic discipline, and should emphasize both doing and knowing. Engineers clearly worked in the human realm and were more valuable in their practice if they could manage both human and material resources. The concluding sentence neatly summarizes these definitions: "…the modern conception of the professional engineer, not as a conglomerate of classical scholarship and mechanical skill, but as the creator of machines and the interpreter of their human significance, well qualified to increase the material rewards of human labor and to organize industry for the more intelligent development of men." (Wickenden et al, 1930).

It would be almost five decades later that the next major policy paper on engineering education emerged. This was the Grinter Report (1955), which was released at a time of growing U.S. global hegemony and a very rapid pace of economic expansion. Grinter shifted the focus of engineering education from focusing on the scientific, technical and human elements of industrial production to the actual scientific basis of the engineering itself. The goal of engineering was the application of science, and thus creative work and research started to occupy an elevated status, soon rising to the peak. The new emphasis was on research for the purpose of discovery and creation of new products and processes. This report saw the main role of the engineer as the provider of technical advances to the larger economic system. Engineering education was conceptualized as being predominantly technical with a concomitant de-emphasis of the humanities and the social sciences. There was also the development of the two tier system, with the creation of undergraduate and graduate education and degrees.

In 1964, the National Academy of Engineering (NAE) was founded under the umbrella of the National Academy of Sciences, and a national conference was held in 1966 to determine what role the NAE should play in engineering education. Presentations were made by various engineering education stakeholders, including representatives from industry and academia, the Engineering Council for Professional Development (ECPD, which would later become the Accreditation Board of Engineering and Technology (ABET)), the American Society of Engineering Education (ASEE), as well as others. There was little consensus that emerged from that national conference. This is reflected in the tensions even in the definitions of engineering: should engineers address technical or social problems? What was the role of the engineer to be in the future? The picture one drew from a reading of these reports from that period was that engineering education was in a crisis, unsure exactly where it wanted to go and what it wanted to be (Walker et al, 1968).

Almost two decades later, the NAE again came out with a report on Engineering Education and Practice in the United States (EEPUS, 1985), which summarized a series of NAE panels and workshops under the umbrella of the Committee on Education and Utilization of the Engineer. Interestingly, in this rep0rt the conceptualization of engineering broadens tremendously, with the recognition of engineering as a system function than a role or a profession. Engineering purpose was re-imagined to mean to serve necessary technical functions in a much larger system, and the report viewed the role of the engineering as very much a member of a multidisciplinary team including management and technicians. The paradigm shift was in placing the engineer within the context of a larger economic and social system, and acknowledging the need for the contextualization of the definition of what an engineer was and did. Thus, the emphasis on preparation of an engineer was that the technical preparation was to occur within a social context, with a large emphasis on the ability of the educated engineer to function on an interdisciplinary team (Davis, 1985).

Our most recent and current definition of engineering and engineering education now come from the NAE report "The Engineering of 2020". The report's definition of engineering is worth quoting here: "Engineering is a profoundly creative process. A most elegant description is that engineering is design under constraint. The engineer designs devices, components, subsystems, and systems and, to create a successful design, n the sense that it leads directly or indirectly to an improvement in our quality of life, must work within the constraints provided by technical, economic, business, political, social and ethical issues." The purpose of engineering was re-defined to be a component in the system, the creative element of a socio-technological system, with the main charges of increasing prosperity and averting catastrophe! Engineers were no longer just solvers of narrow focused technical problems; instead engineers have an obligation to advance technological breakthroughs for the betterment of life, take leadership in the problem solving process and to be able to focus on tackling societal problems. The emphasis in terms of the preparation of an engineer was now to be able to function on multidisciplinary teams to address the major challenges and issues within socio-technical systems. The preparation of an engineer now included the ability to lead and manage within these multidisciplinary teams to address the grand challenges facing human kind.

Considering this abridged history of the evolution of engineering education to its current form requiring that certain well defined student educational outcomes (Table 1) are achieved, it is clear that both creative thinking skills and critical thinking skills are essential components of the skill-set of an engineer today. Critical thinking skills can be developed in students by articulating what exactly it means to be able to think critically. When challenged with a problem, the critical thinking approach is to first seek clarification on the issues. This includes questioning the assumptions made, as well as questioning the viewpoints and perspectives from which one approaches the problems. Critical thinking requires that our approach be based on reason and evidence, logic and data. And perhaps most important, to be objectively critical, one must also probe the implications and consequences of suggested solutions and approaches. Creative thinking, on the other hand, requires the problem solver to be able to ask pertinent "What if…?" questions, and being able to probe the extent and reach of a particular solution.

In this paper, we report on the use of open-ended design (OED) type projects at both the freshman and senior level to foster and develop creative and critical thinking skills in students in our program. At the freshman level, these OED type projects are assigned to four-person student teams in the Introduction to Chemical Engineering Design course, which is the second semester freshman introductory course in the Bachelor of Science in Chemical Engineering (BSChE) four-year program. The students in this course at this level have already had Calculus I and are in their second semester of general chemistry, and the projects involve solving simultaneous algebraic equations using the POLYMATH software package.

Table 1: Accreditation Board of Engineering and Technology mandated student educational outcomes for accredited engineering undergraduate degree programs

a)	an ability to apply knowledge of mathematics, science, and engineering
b)	an ability to design and conduct experiments, as well as to analyze and interpret data
c)	an ability to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability
d)	an ability to function on multi disciplinary teams
e)	an ability to identify, formulate, and solve engineering problems
f)	an understanding of professional and ethical responsibility
g)	an ability to communicate effectively
h)	the broad education necessary to understand the impact of engineering solutions in a global, economic, environmental, and societal context
i)	a recognition of the need for, and an ability to engage in life-long learning
j)	a knowledge of contemporary issues
k)	an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

At the senior level, the OED projects are assigned in the Chemical Reaction Engineering course. These projects are senior level projects involving kinetics, mass transfer, heat transfer and reactor design, and require the simultaneous solution of ordinary differential equations. Differential equations is a pre-requisite for the senior level course and so the students have the theoretical preparation. Senior students also use the POLYMATH software, taking advantage of POLYMATH's ordinary differential equation solver.

Referring to Table 1, the OED projects address several outcomes and such problems can be used effectively to assess student achievement of those outcomes. First and foremost, outcome (a) is addressed, as the development of the project report for the OED requires the application of scientific, mathematical and engineering knowledge. Application of this knowledge is demonstrated by the students by their conceptualizing a system, applying a fundamental principle to develop a model for the system including determining parameters that affect the behavior of the system, and outcome (e), identifying, formulating and solving the engineering problems presented in the OED project. At both the freshman and senior levels, student teams are required to develop a project report addressing the deliverables expected from the OED. This written report addresses outcome (g), the ability to communicate in writing effectively. In the senior course, student teams also make oral presentations of their project reports, further addressing the communications outcome. Finally, to develop their reports, the students must "run" their models under various scenarios of system parametric variation. This requires multiple solutions of, in the case of the freshman, systems of algebraic equations that are the mass balances for the systems they are investigating in their OEDs, and in the case of the seniors, systems of ordinary differential equations that are the mole balances for the reacting systems the senior students are investigating. Students can chose to use the supplied POLYMATH software with it's fairly straightforward user interface, or they use MATLAB, in either case demonstrating outcome (k), which is the ability to use a modern engineering tool (POLYMATH or MATLAB) necessary for engineering practice. Critically structuring the OED project, at both levels, to ensure that these outcomes are addressed is possible by clearly articulating the set of expectations and deliverables that the student teams must work together to develop and submit, and present, in the case of the seniors.

2. Methods

Freshman Course

The freshman course is the Introduction to Chemical Engineering Design second semester core chemical engineering course that our freshmen are required to take. In this course, the basic mass balance equation is presented and student's work on several problem sets to gain familiarity with the concept and it's application. In the open-ended design project, they work in teams to investigate the behavior of a system for seawater desalination involving a membrane unit. The parameter they are asked to vary is the concentration of salt in the produced brine, and to investigate how changes in this affect the amount and rate of freshwater production. A second open-ended project, involves the processing of wet sludge for dewatering, by processing it first through a centrifuge and then a dryer. The parameters for this system include the amount of water the centrifuge can remove and the amount that remains to be removed in the dryer to achieve the process design objective of a dried sludge. The open-ended project assignment is shown in Figure 1.

Senior Course

The senior course is the Chemical Reaction Engineering course, a core senior-level course in our BSChE program. In this course, students have three open-ended design projects that they must work on in groups. The first involves the straightforward modeling of a 2-species predator-prey system, in this case an island with an infinite supply of grass for rabbits, who only have foxes as a their predator. This simple system get students used to the idea of developing a system of ordinary differential equations governing the variation in time of the populations of predators (foxes) and prey (rabbits) and then programming that system of equations into POLYMATH and solving the system of equations with varying parameters, in this first case the birth and

INTRODUCTION TO CHEMICAL ENGINEERING DESIGN
CHEG 102 / SPRING 2017
ASSIGNMENT 7
OPEN ENDED PROBLEMS

1. In one of your recent quizzes, you were presented with a problem where two tons per hour of a wet sludge with 30% solids was centrifuged to give a 50% solids sludge which was then dried in a drier to give a 5% moisture powder.

In this process, moisture was lost in the centrifuge and the evaporator. Now consider the situation if you were an engineer in charge of such a facility with the difference that this facility should be able to take in wet sludges with varying moisture content. Using POLYMATH, MATLab or other software, investigate how the total amount of water removed from the centrifuge and the drier would vary as a function of inlet moisture content. Needless to say, the actual content would vary depending on the solids content of the centrifuge output prior to the drier. You can hold the output moisture content of the centrifuge fixed at various values and plot the variation in moisture removed from each unit as a function of incoming moisture content.

2. In the purification of fresh water from seawater, fresh water is removed through reverse osmosis (RO), distillation or freezing. In a process design submitted to you for review, seawater enters at a feed salt concentration of 20% (w/w). Fresh water and brine leave as separate streams from the RO unit. Assume an inlet feed rate of 100 tons/hr.

Show how the total amount of pure water produced varies with the concentration of salt in the brine.

YOUR RESULTS FOR BOTH PROBLEMS SHOULD BE SUBMITTED AS A REPORT INCLUDING THE PROBLEM STATEMENT AND ANALYSIS RESULTS DEPICTED THROUGH A SERIES OF GRAPHS ALONG WITH DISCUSSION OF THE TRENDS THAT YOUR INVESTIGATION OF THE SITUATION REVEAL

DUE: THURSDAY, APRIL 27th, 2017.

Figure 1: Freshmen Level Open Ended Design Project

death rates of the rabbits and the foxes (Fogler, 2006).

The second open-ended project requires the student team to investigate the behavior of a membrane reactor (MR) and comparing the MR to a regular plug flow reactor (PFR). Student teams must develop the mole balance equations for the two reactor configurations and determine what kinetic, mass transfer and process parameters affect the behavior of the system. After developing the model equations, student teams then investigate, through the utilization of POLYMATH or MATLAB, how the variation in the different parameters affect the outputs from the model they developed. This OED project is shown in Figure 2 (Fogler, 2006).

The third open-ended project for the senior students involves the investigation of a continuously stirred tank reactor (CSTR) in which an exothermic reaction is taking place and the reactor is a jacketed vessel with heat exchange occurring. In this project, the students work to develop the mole and energy balances for the continuous flow reacting system and then simultaneously solve the mole and energy balances in their model, while varying the various parameters that emerged as governing the behaviour of the model. In this third project, the student teams are expected to both develop a written final report as well as make a presentation on the results of their modelling and investigation of the non-isothermal reacting system they were presented with. This third and final OED for the senior students provides the students a clear opportunity to demonstrate that they have indeed achieved the outcomes that were articulated earlier in this paper pertinent to this senior level core chemical engineering course.

CHEMICAL ENGINEERING KINETICS CHEG 403
FALL 2016

10/13/2016
Open Ended Design Problem/Computer Modeling Assignment No.2

Investigation of reaction and mass transport in an inert membrane reactor with catalyst pellets on the feed side (IMCRF). (See Chapter 4.9 in Fogler, 4th Ed)

The reversible isomerization A ⇔ B is being carried out in an IMCRF membrane reactor. The membrane characteristics and that of component B make the membrane impermeable to component A. The data for the system are as follows:

First order reaction: Specific rate constant = 0.05 s^{-1}
Transport Coefficient: k_c = 0.3 s^{-1}
Equilibrium Constant: K_e = 0.5
Feed volumetric flowrate to IMCRF: v_o = 10 dm^3/s
Feed concentration, C_{Ao} = 0.2 mol/dm^3

Answer the following questions:

1. **What is the equilibrium conversion if we assumed B could not diffuse out of the membrane?**
2. **Plot conversion profiles to compare a 100 dm3 conventional PFR with a 100 dm3 membrane reactor. What statements or generalizations can you make? What parameters have the greatest effect on exit conversion from (1) above.**
3. **Plot conversion, species concentration and molar flowrate as a function of reactor volume/length.**
4. **Vary the kinetic, equilibrium and mass transport parameters in a co-ordinated and logical manner and discuss your results in a maximum of one page.**

The deliverable, as for the 1st Open Ended Design problem, is the problem statement and set-up, answers to each of the above questions, printout of your model equations, printouts of relevant results, and a maximum of 1-page (typed double spaced) discussing the results of your analysis for question 4.

DUE DATE: Thursday, November 10th, 2016

Figure 2: Senior Level Open Ended Design Group Project Assignment

Student Outcomes

Student achievement of outcomes in both courses was assessed through group project reports and presentations. In terms of the open ended solution developed, students were assessed on the adequacy of the model equations to characterize the system, the appropriateness of the choice of system parameters to vary including an adequate range of parametric variability, the pertinent choice of model outputs to report, the interpretation of the results, the deduction of second order results and the ability to coherently

CHEMICAL REACTION ENGINEERING - CHEG403/FALL 2016
OPEN ENDED PROBLEM PRESENTATIONS STUDENT OUTCOMES EVALUATION

Group________________ Members ______________________________
____
____
____
____

Evaluation Conducted by:______________ on Date: ____________

Students are rated as Low (L), Medium (M), High (H) or Very High (VH)

Evaluation of individual achievement of each outcome is based on rubric for Open Ended Group Problem solution provided in the Assignment Statement for report and presentation, as outlined below:

Group Member Student Names →	___	___	___	___	___
Was the team professionally attired and did they present themselves as such?					
Did they introduce themselves and identify their roles and responsibilities? Did they speak slowly and clearly and articulate their elocution?					
Did they introduce the chemical reactor problem and describe the reactor system and their approach? Did they show the reactor system system and present the kinetic and model equations? Did they choose relevant variations of identified parameters to investigate the impact on the reactor models behavior? Did they display appropriately labeled and captioned figures of the results of their investigations?					
Did they discuss the impact of the parameter they studied and point to possible trends? Did they integrate their individual discussions to develop an overall discussion of their results?					

Student Names →	Student ___	Student ___	Student ___	Student ___	Student ___
Outcome (a): an ability to apply knowledge of mathematics science, and engineering					
Outcome (e): an ability to identify, formulate, and solve engineering problems					
Outcome (f): an understanding of professional and ethical responsibility					
Outcome (g): an ability to communicate effectively Outcome (k): an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice					

COMMENTS:____

Figure 3: Student Presentation and Report Evaluation of Outcomes Achievement: Students are rated as achieving the outcome at the Low, Medium, High or Very High level

report as group on the findings in the form of a group project report and, in the case of the seniors, a presentation. The evaluation and assessment table completed for each student team is presented in Fig. 3.

Creative and Critical Thinking

When presented with the open-ended nature of the project assignments, the students have to exercise their creativity in choosing what range of parameters they use in the development of their solutions and in production of their final project report. And their critical thinking skills are exercised as they interpret and analyze the outputs from the computer model experiments they run and as they extract second order results from their analyses, showing how parametric variation affects system behavior and outcomes. It is insufficient for the student teams to present the direct results of the solutions of the model equations for several values of different parameters. As students are reminded, these are straightforward first-order results that come directly from the outputs of the model solutions, and, for a report to meet standards demonstrating analytical and critical thinking, second order results that need to be extracted from the direct outputs from the models solutions also need to be presented. Thus students cannot simply turn in outputs from their POLYMATH runs; they need to take these outputs, further analyze them to extract and develop second order model results, which must be included in their reports and their oral presentations.

Conclusions

3. Creative and critical thinking skills need to be developed in engineering students in order for them to be successful in today's socio-technological environment. Incorporating open ended design type projects that students work on in teams is one way for these important employability skills to be encouraged and fostered in engineering students.

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