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Capstone Design Projects: An Emphasis on Communication, Critical Thinking, and Analysis

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Work In Progress

Our department has adopted the following Program Educational Objectives, such that within three to five years after graduation our graduates will have demonstrated Competency in the discipline of chemical engineering; exhibited Critical thinking ability that has enabled them to solve complex problems; successfully achieved Cooperation goals through teamwork; demonstrated effective Communication and will have exhibited the Capacity for life-long learning. With these objectives in mind, our undergraduates have a wide variety of experiences, which support student outcomes, which define the set of learning outcomes representing knowledge, skills, and behaviors students should possess by the time of graduation in order to achieve the Program Educational Objectives. One of our specific student outcomes is to solve and analyze open-ended problems and another is to engage in critical thinking by evaluating design solutions. With these outcomes in mind, in our capstone design I course, students are required to design a process, which converts raw materials into a desired product. This process design is completed in teams of 4-5 students and each team designs a different process. The design assignment is split into different sections, which include; process synthesis and balances, equipment design, process simulation and process economics. In order to provide our students the opportunity to effectively communicate their work, critically analyze and critique open-ended designs, the projects are rotated between teams for each section of the design. For the final design, each team is returned their original design project and critiques in order to complete the final analysis. During the rotation of projects, the teams have the opportunity to work on the design of three different processes, to evaluate one another's work, integrate design reviews into their final analysis and learn by critically analyzing the work done by other design teams.

This is the second year of this approach to teaching our capstone design I class. This work in progress presentation will include specific details/examples of course/team logistics, team and individual assessment and direct assessment of learning objectives. In addition, qualitative data analysis software, NVivo will be used to aid in the analysis of the textual materials of the design project reports. Since each team works with and builds upon the work of two other teams, the software will be used to classify, sort and identify themes in student work in order to determine how the final design has evolved over the course of the semester long project. Specifically the software will allow comparisons across teams and design sections, organize and track the team's work and will allow a qualitative analysis of the evolution of the final design. In addition, the technical evolution of the design will be quantified by examining the design changes in response to the critiques provided by the other teams.

Introduction

Our department requires a two-semester capstone design course – the second semester capstone course requires all of the student teams to work on the same design project (usually one of the AIChE contest problems) all semester long and the course concentrates on oral communication. Over the last ten years, the first semester capstone design course has been taught by a variety of part-time faculty members most of whom had industrial experience, and recently has been taught by the author, a full-time faculty member with industrial experience, specifically in process engineering and plant design. While mentoring new engineers in industry, it was observed that they often lacked experience in being able to critically analyze and critique work performed by other engineers. In an effort to provide this experience before graduation, the first semester capstone design course was completely restructured.

Course Structure and Grading

The course is three credits and met three days a week for 50 minutes. The Monday and Wednesday classes covered the following topics (which included numerous presentations by industrial experts):

- Process Synthesis
- Process Heuristics
- Equipment Design
- Sizing Catalytic Chemical Reactors
- Pinch Analysis
- Process Simulation
- Economic Analysis
- Sustainability/Life Cycle Analysis
- Chemical Engineering Unit Operations and Troubleshooting
- Engineering Ethics

These topics and structure align well with the most recent surveys of how engineering capstone design courses are taught[1-5]. The Friday class period was designated as “Design Team Friday” and the teams worked on their projects. During these class periods the course instructor, two teaching fellows (super seniors who had taken the two semester capstone design courses the previous year), and ‘guest consultants’ (who have industrial design experience) met individually with teams to assist in their designs, help with critiques and discuss/resolve conflicts.

The course consisted of both individual and teamwork. This allowed for the assessment of professional skills[6] essential for the fulfillment of ABET criteria. Grading in the course consisted of the following deliverables:

- Individual Exams
- Completion of four SACHE certificates
- Three Project Reports (Team)
- Peer Project Evaluations (Team and Individual components but Individual grade)
- Individual Progress Memos
- Final Project Report (Team)
- Final Project Presentation (Team and Individual presentations but Individual grade)

The individual’s grade for the project was calculated from the Team Project grade and weighted using the evaluations of the individual’s contributions to the team effort made by the team members. The teams were created using CATME[7,8], which allowed the teams to be formed so that each team would have common schedules to work on the projects (multiple days a week with at least two hour time blocks), as well as to balance the teams academically, by gender and diversity. CATME is an extremely useful tool in creating teams, since it allows the user to manually separate students into teams – this was essential since our students have worked in teams in at least seven previous courses in our curriculum and conflicts have evolved – therefore, students were separated to avoid known conflicts. Teams were also balanced by academic performance, students with internships, students minoring in economics, students who are in our three different tracks (traditional, bioengineering and environmental engineering), as well as to create teams who have available blocks of time in common. In addition, CATME was used to collect and analyze self and peer evaluations of team members' contributions. Students were required to complete the CATME survey at the end of each of the four project report milestones. Also, students were required to individually complete memos to the instructor, which outlined their individual contribution to the design, documented the team meetings and distribution of labor and provided a grade for the report, which they had received and reviewed. This memo was separate from the Individual Progress Memo.

Each Individual Progress Memo required the student to address four specific prompts with each iteration: (1) What is your personal understanding and analysis of the work you have done toward the most recent project? (2) What was your personal contribution to your team's accomplishments? (3) How has your most recent work affected or reflected the overall process design and economic analysis? (4) What are the next steps you will personally take in completing this project, and what questions will you be seeking to answer? The students were required to be both precise and concise in their response so that it accurately reflects their ability to work with this project and its fundamental engineering principles. The students were provided formatting requirements and a detailed grading rubric(9).

Design Projects

As stated previously, the objective of the rotation of projects between design teams were fourfold: so that the students 1) would have the opportunity to work on three different processes 2) gain experience in evaluating one another's work 3) to integrate design reviews into their final design and analysis and 4) to learn to critically analyzing the work done by other design engineers. Each team worked on a separate design project (selected by the team). At the beginning of the semester, an over-view of each of the design milestones was provided so that teams could select their raw materials/products with a full understanding of the work that they would be required to complete. Each of the projects had to be approved by the course instructor and the design projects had to(10-12):

- be challenging
- have a good chance for successful completion
- have data available in the literature
- emphasize the application of theory
- involve engineering design work
- meet specified safety criteria, and
- not rely on proprietary information

The teams were provided a detailed grading rubric(13) and design project report guidelines, which were used to develop the reports and the team/individual assessments. Each of the design project milestones consisted of:

Design Project 1:

Each team was required to design a process, of their own choosing, which converted raw materials (of their choosing) to a desired product (also, of their choosing)[14]. This allowed the teams to identify the primary levels of engineering design. They were required to apply synthesis methodologies to determine the input-output and recycle structure of the process flow sheet. At a minimum, each process included:

- A reactor with catalyst
- Incorporation of recycle streams to maximize reactant conversion
- Incorporation of a separation system(s)
- Heat exchange network (with the eventual goal of applying heat integration principles to conserve energy)

The following deliverables were required for the first design project report:

- Identification of raw material costs and selling price of the product
- Detailed process flow diagram with all major pieces of equipment identified and conditions specified
- Develop and effectively communicate the material and energy balances for the process (and each major piece of equipment).

Design Project II

Each team had to provide detailed design calculations, specifications and cost of the equipment corresponding to the 'new' process that they were assigned to review and grade. This allowed each team to analyze a new process and verify the process flow diagram, material and energy balances and corresponding references. Each team had to provide an evaluation (one-page critique) of the first design report and calculations. In addition, individually, each team member had to provide a grade sheet and evaluation (with comments as necessary), using the grading rubric provided.

Then, each team had to prepare design project #2, which built upon the design results of project #1, and provide the detailed design calculations, specifications and cost of each piece of equipment of the new process. The teams were required to include any corrections, which were identified for the first design. The second design project required detailed equipment data sheets (and supporting calculations for each piece of major equipment for the process). The data sheets, at a minimum, included:

- Equipment identification
- Function
- Operation
- Materials handled
- Basic design data with size specifications
- Installation requirements
- Allowable tolerances
- Pertinent details

The following deliverables were included in the second design project report:

- Any required corrections to the first design project
- Develop and effectively communicate the major equipment designs

- Equipment data sheets and supporting calculations
- Equipment costs

Design Project III

Each team was required to develop a working steady state ASPEN simulation of a third process, which they were assigned to review and grade. This allowed each team to analyze a new process and verify the process flow diagram, material and energy balances and detailed equipment design, which were performed by other teams. In addition, each team had to provide evaluations/critiques for the first two design projects – and each individual graded each of the first two design projects. In addition, each individual was required to provide an assessment of the individual team member's contribution and distribution of labor for the first three projects.

The third design project built upon the first two design projects (and provided any necessary corrections) and included the simulation of the original process. The design project three report included the results of the simulation (including the mass and energy balances), and once a steady state model had been developed, the results of the sensitivity studies were used to:

- Reduce process temperature and pressures
- Apply heat integration methods to conserve energy
- Incorporate recycle streams to maximize reactant conversion

The following deliverables were included in the third design project report:

- Any required corrections to the first and second design project
- Develop and effectively communicate the simulation of the new process
- Provide the results of the sensitivity studies

Design Project IV (Final Project)

The final project, required each team to develop a complete economic analysis of their original project. This economic analysis required any revision of the original process flow diagram, material & energy balances, corrections to the equipment design calculations, specifications and costing, as well as modifications to the simulation of process. This allowed teams to re-analyze the original process and analyze additions and changes that other teams proposed for the process. Each team was required to provide evaluations of the second and third design project reports and calculation; including a one-page critique for each of the reports and work provided. In addition, individually the team members provided grade sheets for reports two and three, as well as their assessment of the individual team member's contribution and distribution of labor for the final design project.

The final design project, again, built upon the first three design projects (evaluations and critiques) and required the economic analysis of the original process and a review of the detailed design calculations, specifications and cost of each piece of equipment, and simulation of the original process. The final project was required to include any corrections, which had been identified in the previous two design reports. At a minimum, the final design project and economic analysis, included the following:

- Raw Material Costs
- Equipment Costs
- Production Costs
- Working Capital

- Projected Revenues
- Payback, Return on Investment

The following deliverables were also included in the final design project report:

- Any required corrections to the first, second and third design projects
- Develop and effectively communicate the complete process flow diagram, material and energy balances, detailed equipment design specifications and cost, simulation and optimization, and economics of the original process.

Reflections on Teaching Capstone Design

The author has been fortunate to teach a wide variety of courses in our curriculum – from the multidisciplinary freshman engineering design course to the material & energy balance course to the junior year transport course to the senior year capstone design course. This has been a great opportunity to help the students make progress with their engineering skills, and to witness their development over their entire college career. Up until capstone design, the students usually solve clearly defined technical problems while selecting appropriate mathematical relationships. In contrast, design requires the students to use different skills, which rely much more on practical knowledge – which is why an effort was made to distribute students with internship/industrial experiences to each of the design teams. Along this same vein, the class content was focused on sharing the authors and guest consultant's industrial experiences[15] in each of the topic areas.

In recent years, our class sizes have more than doubled – which has made this approach of having all of the teams work on different design projects even more challenging[2]. However, the tradeoff of having the students exposed to a wider variety of processes made this effort worthwhile. Keeping track of many different processes and designs was essential in providing the team timely and constructive feedback that focused on the development of conceptual understanding, professional skills and the integration of knowledge and skills. The students were provided rubrics[16] for self-assessment and the work done by other teams. In the first year when the revised course was taught, each team provided both a critique and a team grade for the projects that they received. This was revised in the second iteration, to consist of a team critique and an individual grade, since it appeared that the team grades were artificially low and sometimes seemed vindictive and not consistent with the critique. It was observed in the second year, the critiques remained fair and the individual grading was much more in line with the critique.

The author, teaching fellows and guest consultants spent most of the Friday sessions mentoring the teams – not just acting as design consultants, but also helping to resolve issues associated with their critiques and helping them to function as a coherent team. Many of the CATME scores indicated that there were students who were 'high performers', 'over and under confident', but there were also teams with students who were 'manipulators' and had 'personality conflicts'. Time was spent with the teams to develop strategies[17,18] to resolve these issues for the next round of the design project.

Our department has had a long tradition of introducing our students to simulation (ASPEN) and computing/modelling software (MATLAB/COMSOL) prior to the capstone design courses. As such, many of the teams initially wanted to use these tools to model their system in the first iteration of developing the process flow diagram and material & energy balances. It has been the authors' experience that students often are quick to use these tools, and not take the time to critically analyze the results of the simulator[19,20], and simply take the computer results as 'correct'. Therefore, the teams were ***required*** to complete their material & energy balances by 'hand' (i.e. not using ASPEN, but using spreadsheets). This gave teams a better understanding of the assumptions/calculations that they were making regarding the phase, reference conditions, etc. for each stream.

Assessment

As this work is still in progress, the qualitative data analysis using the NVivo software, has not been completed. It is anticipated that the analysis of the textual materials of the design project reports will be presented in the poster session. Since each team works with and builds upon the work of two other teams, the software will be used to classify, sort and identify themes in student work in order to determine how the final design has evolved over the course of the semester long project. The software allows comparisons across teams and design sections, organizes and tracks the team's work and allows a qualitative analysis of the evolution of the final design. The technical evolution of the design will be quantified by examining the design changes in response to the critiques provided by the other teams.

Anecdotally, the author has observed significant positive changes in the readability and technical merit of the design reports over the four phases of each of the designs. Formatting and flow of content also provided positive improvements of the design reports from the first report to the fourth report. In addition, at the poster session, the direct assessment of learning objectives will be presented, as well as the students' surveys results, which will provide comparisons for students who have completed both capstone design courses with those who have only completed one capstone design course.

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