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Chemical Engineering Capstone Course Improved for Broader Impacts

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Robert Enick

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Introduction

Capstone courses for chemical engineering students are generally based on process design targeting a grass-root design of a commercial size plant to convert raw materials into valuable products. Most institutions offer a single or two semester-long courses, with an average of about 4 h/week dedication split between lecture and process simulation [1]. They have been frequently taught by faculty with industrial experience or with the support of industrial partners in some associated role [1]. Students are mainly requested to work out in 3-4 member teams with projects sponsored by industry, faculty, and institutions (like the AIChE design challenge) or based on textbook or other literature source [1]. An essential component of those projects is the use of process simulation software (mainly Aspen), with additional support from some other mathematical software (EXCEL, MATLAB) [1]. The use of textbooks is very diverse, but some are very popular like Turton et al. [2]. The dominant technical content of the course (process design, simulation, economics, heuristics, synthesis, plant design, energy integration, optimization) has been increasingly enriched with professional skills (i.e., teamwork, project management, organizational skills, conflict resolution), ethics, and a broad coverage of safety topics (i.e., flammability, chemical reactivity, HAZOP, pressure relief), with some institutions exploring multidisciplinary approaches (like integrating students from other engineering disciplines) [1]. This broad variety of topics and skills attempted in these courses, with the attempts to recap content from previous courses in the curriculum favor the use of this course for the assessment of ABET outcomes [1].

Frequently, faculty show concerns on the class size, the quality of the project assignments, and the weaknesses of students (i.e., lack of motivation, poor dominion of previous courses, lack of teamwork skills, and inability to handle open-ended problems). They constrain reaching goals for higher-level skills like critical thinking, problem-solving and fundamental competency [1]. Some teachers have also been concerned with entry-level engineers in industry lacking skills on critically analyze and critique work performed by other engineers, and have implemented a rotation of three preliminary design projects where teams review previous and advance new steps in different projects before completing the final report of their former process [3].

Recent research has shown that a large percentage of chemical engineering faculty consulted in an extensive survey perceived significant deficiencies in teaching ethics and broader impacts in undergraduate education [4]. They also identified capstone courses as the most common course to include these topics [4]. The importance of integrating ethics and societal impacts in undergraduate education is highlighted by ABET criteria 3 outcome (4): “an ability to recognize ethical and professional responsibilities in engineering situations and make informed judgements, which must consider the impact of engineering solutions in global, economic, environmental, and societal contexts” [5]. Similarly, the importance of including broader impacts in engineering design is emphasized by ABET criteria 3 outcome (2) “ an ability to apply engineering design to produce solutions that meet specified needs with consideration of public health, safety, and welfare, as well as global, cultural, social, environmental, and economic factors" [5].

This paper elaborates on our current efforts to integrate broader impacts in the capstone Process Design course. It summarizes the technical content of the course based on the grass-root plant design for a mid-size commercial production of styrene. It is intended to exemplify the technical skills covered in the course. It also describes some accompanying skills like teamwork and communication skills associated with the technical content. Then it introduces the approach for broader impacts, mainly (a) a social impact report, where students examine societal impacts for two potential sites for the plant (one in the US, one in a foreign country of their choice), (b) a poster as a communication piece to introduce the project to a potential audience of the community around a selected site for the plant, (c) an outreach project mainly targeting a K-12 nearby community to show the attractiveness in developing a college career in engineering, (d) a networking project on a one-to-one basis with alumni to get advice and mentorship on developing a professional career in engineering, and € a practical experience on a "virtual office" model to reinforce teamwork skills, leadership, and coaching.

Content structure and strategy

Our department has a long tradition of experimenting and innovating in the structure and strategies for the capstone process design course [3]. Currently it is a one semester long 5 credits course offered in the spring (two sections) and the summer. Class sizes have varied widely from 15 students in the summer session to over 50 students in each section of the spring session. One section has been taught by the same instructor for the last seven years with the structure and content reported elsewhere [3]. The other spring section and summer session has been evolving through the years with various instructors introducing some variations over a basic backbone structure and content as reported here. A companion course on Ethics and Safety, 2 credit units, complement in many aspects, and extensively relates to the design course.

Class meets three times a week in 1h50m sessions mainly to deliver lectures on the various topics of the course as outlined below. In addition, another 1h50m weekly session is devoted to process simulation and teamwork. The instructor occasionally introduces some changes in this sequence to accommodate to the progress of the project and match up content with simulation step. The classroom is configured with a technological setup of twelve 6-seat semicircular tables provided with three desktops each interconnected to a mainframe with the licensed programs accessed through a VIRTUAL LAB platform. Instructor's podium is set with two tables also provided with one interconnected desktop, projector, and large screen each. Instructor's computers can take over students' computers to deliver content or assessing ongoing work. In addition, the classroom is provided with an audiovisual system for recording and livestreaming.

The course requires successful completion of previous courses on mass and energy balances, basic unit operations, thermodynamics, transport phenomena, and reaction kinetics. It follows all the dominant characteristics reported before for teaching this course [1], maybe with the only difference of the 5–6-member team structure to accommodate the increased demands on time and work as illustrated below.

The course is introduced by a 40-pp. syllabus with detailed information on description, outcomes, schedule, bibliography, lecture outlines and specific skills to develop, requirements, assignments, reports' content and formatting, grading, projects, teamwork, technology, and academic policies.

The technical content follows a synchronous dual path: theoretical and practical lessons on process and plant design, and a design project for a commercial midsize plant to produce styrene (by dehydrogenation of ethylbenzene) by a sequence of steps that follow the lectures' content. The lectures' content follows the sequence: 1. General approach to process design. 2. Process diagrams. 3. Process Flow Diagrams (PFD) structure and synthesis. 4. Mass and energy balances. 5. Batch processes and scheduling. 6. Product design. 7. Tracing chemicals. 8. Process conditions. 9. Experience-based principles (heuristics). 10. Pinch technology. 11. Exergy (lost work). 12. Materials of construction. 13. Reactors. Packed Bed Reactor design. 14. Distillation columns. 15. Heat exchangers and fired heaters. 16. Storage tanks. 17. Three-phase (LLV) separators. 18. Pipes and valves. 19. Pumps and compressors. 20. Economic evaluation. 21. Estimation of capital cost (equipment cost). 22. Estimation of manufacturing cost. 23. Engineering economic analysis. 24. Profitability analysis.

The design project integrates a series of information and simulation sessions. 1. Project basis (description and sections). 2. ASPEN software access, description, chemical components, properties estimation methods, and equipment configuration. 3. ASPEN model configuration of streams and equipment. 4. ASPEN simulation of raw materials processing (including mixers, splitters, heat exchangers, and reactors). 5. Analysis of results of ASPEN simulation runs. 6. ASPEN simulation of separations section (including three-phase separator, distillation columns, and gas burning section). 7. ASPEN simulation of traditional (non-optimized heat integration) plant. 8. ASPEN simulation of optimized heat integration plant (following pinch analysis). 9. ASPEN simulation of catalytic reactor, supported by thermodynamic analysis ("Gibbs" reactor). 10. ASPEN simulation of distillation columns including sizing and internal configuration. 11. ASPEN simulation of heat exchangers with complete TEMA specification sheets by AEDR (Aspen Exchanger Design and Rating software). 12. ASPEN simulation tools to assess some issues on storage tank safety (i.e., flammability limits). 13. ASPEN simulation tools to assess pumps and pipes design. 14. AVEVA 3D simulation of the traditional plant version of the design (open to explore sizing and spatial perspectives). 15. APEA (ASPEN Process Economic Analyzer) simulation for equipment costs, manufacturing costs, and plant profitability analysis.

In addition, a series of short lectures on professional skills has been introduced though some of them have been left aside when time constraints impose some limits. 1. Literature search and databases. 2. Engineering design process. 3. Teamwork. 4. Leadership. 5. Collaboration. 6. Green engineering. 7. Safety. 8 Ethics and professionalism. The last two topics are covered with larger extension at the companion course on Ethics and Safety.

This content has been delivered in-person and on-line, as requested to adapt to COVID-19 restrictions.

Student work, projects, and outcomes

Students are expected to attend every class, participate in every recitation (simulation sessions), and monitor the content posted in CANVAS, including the slides of every lecture for reviewing, and the assignments. The previous lecture is reviewed at every new lecture followed by a short

(6-7 questions) on-line quiz on TOP HAT for 316 items through the course (5% of the final grade).

The main component of the student work is the design project (60% of the final grade) for a grass-root plant design to produce 215 MM lbs./year of styrene monomer (99.8% purity) from the catalytic dehydrogenation of ethylbenzene. The project is distributed in 13 sequential weekly reports (3% of the final grade each, about 10 pages each) as briefly described in Table 1. They follow the timely combination of lectures, notes, and simulations to understand the concepts, generate the data and apply the learnings. Reports are graded on the same weekly basis following a prescribed rubric with additional comments for improvement. A final report (6% of the final grade) consolidates all the progress reports in proper order, including corrections, harmonizing references, and providing a fluent reading as intended for a potential investor. Appendix 1 shows some selected illustrations of the type of content and results developed by students in these reports.

An integral part of the design project is the development of several simulations for process synthesis and design, and for economic analysis. These simulations are developed using ASPEN Plus, AEDR, APEA, AVEVA, EXCEL, and MATLAB. An additional report (5% of the final grade) compiles illustrative examples of all these types of simulations, with descriptive notes and images, and copy of representative files. The landscape format of this simulation's portfolio, with left pages containing descriptive notes of the images in the right pages is intended to provide students with experience in designing "marketing tools" to effectively communicate in the "selling" of their projects and proposals, and to identify the use of simulations as advanced tools for calculations and presentations. The focus of this report is to emphasize the educational and professional training values of simulations, in addition to develop artistic and esthetic skills.

A final 10-minute presentation (5% of the final grade) summarizing the project is delivered to a panel including academic instructors of the course and invited industry representatives with experience in process design. The grading rubric is provided in Appendix 2. The panel adjusts the grade by individual performance at the presentation. In addition, every team must produce a 4-5 pp. critical assessment (5% of the final grade) of one other team's presentation. They are encouraged to analyze the differences in results with their own work, in addition to the assessment of communication skills. The team also fills by consensus the same rubric as the panel. This grading does not affect the grade of the team under evaluation.

The extensive technical content of the course has been expanded with additional perspectives and strategies to improve the formation of graduating seniors as they are close to transition to the job market. They are intended to improve the experience and learning of the course focusing on broader impacts. Taking the words from one report: "There is far more that goes into developing a chemical plant than engineering and economics. A plant is not just an isolated entity, but highly intertwined with the subsistence of its surroundings. Much more needs to be taken into consideration beyond just the safe operation and economic viability of the plant. Such a large production facility has significant impacts on the environment on both a localized and global scale. The development of necessary infrastructure may uproot some local habitats, or the production of harmful pollutants and waste products may negatively impact both people and wildlife. Stepping beyond the physical realm, a plant on this scale may affect the social or cultural norms of nearby communities. It may provide jobs for local workers, or it may be a nuisance to citizens trying to live a more secluded lifestyle. A holistic approach, including these considerations and more, should be taken when evaluating whether the construction and operation of such a large-scale facility is appropriate." [6]

Table 1. Brief description of progress reports for the design project

	Weekly Progress report
1	Process background. Properties and characteristics of materials. Statistics on worldwide production of styrene and facilities. Forms and uses of styrene. General description and comparison of the dehydrogenation of ethylbenzene for styrene production including catalyst types and operating conditions
2	Preliminary BFD (Block Flow Diagram) from basic specifications. Preliminary mass balance. Preliminary PFD (Process Flow Diagram) on an EXCEL spreadsheet with detailed quantitative description of process streams. Revisit this assignment after the plant simulation in ASPEN and analyze the most significant differences
3	Pinch analysis (tabular and graphical approaches) based on an "all utility" plant with added methane for energy requirements
4	Heat exchanger network design based on pinch analysis but reduced to some major streams.
5	"Traditional plant" design based on the previously simplified heat integration. PFD and streams table. Evaluation of utilities and pinch point
6	Detailed plant description. Exergy analysis.
7	Dehydrogenation reactors. Research on kinetics. Thermodynamic analysis. Catalyst sizing. Reactor configuration. Heat transfer and insulation.
8	Distillation columns. Sequencing selection of three vacuum columns and two atmospheric columns. Rigorous description, sizing, and internals.
9	Heat exchangers. Detailed description (TEMA specification sheets by AEDR software) of the two major heat exchangers (feedstock heater and reactor products cooler) and a fired heater (steam generator)
10	Three-phase separator and storage tanks (5) design with safety assessment
11	Pump design and specifications for a selection of major equipment. Examples for pipe sizing and valves selection. 3D Simulation by AVEVA. Experience with perspectives, sizes, and distances.
12	Plant equipment summary including costs and total direct cost by equipment and sections
13	Economic assessment. Profitability analysis and sensitivity analysis for four potential scenarios.

A report on social impacts (5% of the final grade) requires students to consider the public health, safety and welfare impacts of building and operating the plant designed in the project. The safety analysis is embedded in the companion course on Ethics and Safety as a bridge content, incorporating the learning on that course for application to the design project in this course, for a more integrative experience. Students are required to address specifically potential environmental, social, cultural, and global impacts that the plant could bring with it. They are provided with some examples from other processes for reference, but the target is to let them consider in an open-ended assignment all these factors. In addition to the literature search, they can profit from their experiences at co-op rotations in manufacturing industries to come up with topics and circumstances beyond the technical content of the design. Table 2 provides an example of the topics developed by one group [6] in their 20-pp. report.

Table 2. Example of main topics considered in assessing the social impacts of the project for the plant location at Louisiana, US [6]

Public Health
Toxicity and carcinogenic classification of hazardous raw materials and products. Risk of gases release and liquid spills. Mitigation safety procedures can prevent accidents that have been taken place in the past.
Safety
Adequate ventilation and PPE are required for handling ethylbenzene. Fire mitigation strategies (water sprays, dry chemicals, and foams). Preventive system to avoid contamination of aquatic habitats. Protective layer to avoid explosion of highly flammable styrene in addition to avoid ingesting and inhaling styrene (PPE). Prevention of the risk of polymerization by the adequate use of inhibitors at operation equipment and storage tanks. Protective layer to avoid explosion of highly flammable benzene (by-product). Prevention of disposal to aquatic habitats. Some similar safety measures for toluene. Close monitoring of temperature and level sensors at storage tanks to prevent risk of explosions
Welfare
Immense store of high-paying jobs for local communities though controversial allocation for selected specialized manpower
Global
Well established global market for styrene limits new entry companies but increasing demand opens opportunities. Management challenges for multi-countries operation of styrene producing companies. Potential to develop new markets in countries with increasing industrialization. Technology transfer from highly developed countries to less developed countries but rich inn raw materials Increasing competition in technology and marketing Critical impact of supply chain disruptions by pandemics (i.e., COVID) or war conflicts (i.e., Russia-Ukraine)
Cultural
Demands for transparency on informing about potential risks, waste disposal, accidents prevention, and open communication. Provision for fair wages, ability for time off, and equal hiring opportunities to safeguard cultural values like independence, personal freedom, and equality
Social
Plant location in economically disadvantaged areas ends up with poor and marginalized population bearing the burden of pollution associated with chemical facilities (i.e., “Cancer Alley”, Louisiana) Communication with community leaders and representatives to address risks and benefits of plant operation
Environmental
Increasingly stricter regulations for pollutants generation. References to main legislation applicable to raw materials and products from the plant.
Ethics
Behavior in potentially abnormal situations. The risk of compromising safety with productivity. Importance of an explicit code of ethics. Requirements of training and reinforcements on developing a culture of “safety first”. Illustration by previous accidents. Relevance of updated documentation on procedures and proper training.
Professional responsibilities
Extension of responsibilities beyond stakeholders and employees (i.e., community, suppliers, customers, public, global) Caring for profitable operations, fair wages, professional development, community services and support (outreach programs) Monitoring and improving social impacts

To extend further the analysis of these potential impacts the team must consider two alternative plant locations, one in the US (base case for costs and profitability analysis) and one in a different country. The target is to highlight similarities and differences, particularly assessing potential advantages and disadvantages. Calculations are not required but the qualitative trends may add figures on labor wages, tax rates or incentives, land cost, etc. Students are invited to assess how the differences may affect the choice for the selection of plant location. Table 3 provides an example of the topics analyzed by one group on the alternative locations. Selected US locations include Louisiana, Memphis (Tennessee), Texas, Beaver County (Pennsylvania), and Mississippi. Foreign locations considered in the last edition of the course included Mainland China, Sins (Aargau, Switzerland), Germany, Hauts-de-France (France), Maasylakte (The Netherlands), and Jiangsu province (China).

Table 3. Selection of potential advantages and disadvantages when considering an alternative location at a foreign country [6]

Location	Bucharest, Romania (Nearby rural location)
Potential advantages	Potential disadvantages
Proximity to large styrene demand (France, The Netherlands). Advantageous tax rates (as member of the European Union). Low-cost labor force availability. Increasing educational level. Above European average growth rate for the chemical industry. Much less unhealthy competition in the work environment. Less resistance is expected from the surrounding community as population is familiar with the risks (from coal mines, steel mills, etc.) and they are not at the top of their concerns (crime, social tensions, turmoil, shortages)	Lack of current chemical infrastructure. Limited agency in global affairs. High standards of environmental protection from European Union legislation. Contemporary political instability. Dramatic impact of the nearby Russia-Ukraine war and the flooding of Ukrainian immigrants into Romania

In addition, every team must prepare a poster (3% of the final grade) with a summary of the most impactful data and conclusions for the project and a selection of social impacts intended to introduce the proposal to the community where the plant is to be located (either one of the proposed locations). Students are asked to envision the scenario where community representatives approach the invitation from the company to know the plans for building and operating the plant. Public opinion will influence the final approval for the project to be developed in such a location. Data should be presented to gain their approval based on promising impacts on the welfare of the community and sustainable development but without hiding the uncertainties and risks for the community. Students are encouraged to use pictures, drawings, and titles that can attract the attention of the public inviting them to ask questions. Figure 1 provides an illustrative example.

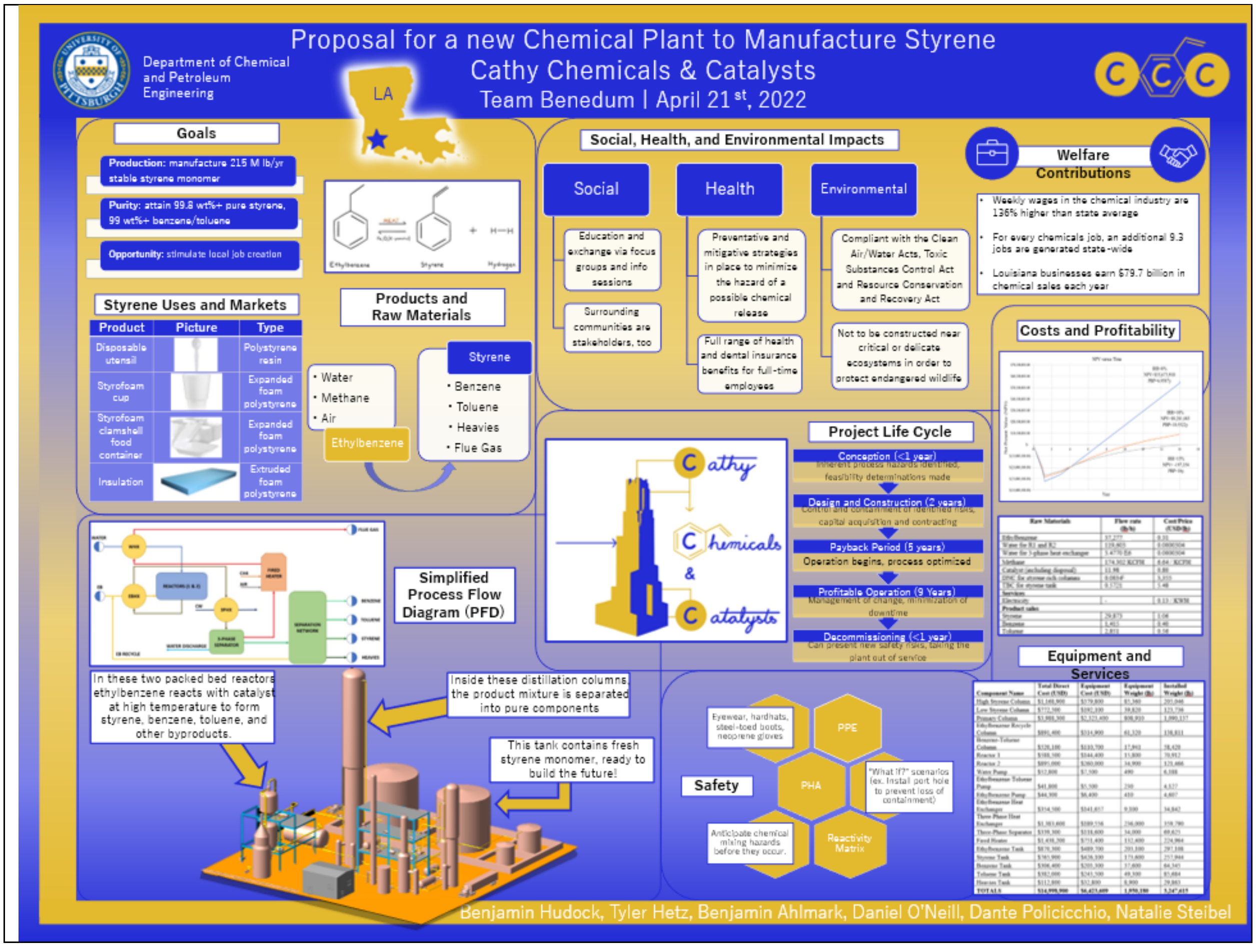

Figure 1. Poster to introduce the project to the community of the plant location [7].

Most of the students taking this course are ready to move into the job market; in fact, many of them attend job interviews during the course of the semester. They are completing the college life cycle after 4-5 years. Most have gained valuable experiences at co-op rotations alternating with their semesters in college during the junior and senior years. They have a unique vital perspective of what it means to become a chemical engineer. All this serves as a strong motivation to ask these students to approach K-12 scholars promoting their potential interest in STEM careers (mainly chemical engineering). They can provide them with some guidance about the college experience and the content of the courses. It has also proved to be very valuable and engaging to show them the co-op and internship experience in the wide variety of industries and research that is open to engineering students. They can work out hands-on experiments to illustrate and make attractive fundamental concepts in engineering curriculum. All this provides the basis for the outreach project (10% of the final grade).

The rationale for the inclusion of outreach projects in the curriculum, the structure and deliverables and their impact on the next generation of students have been reported before [8]. Table 4 shows some illustrative information on the type of communication strategy, content, audience and the number of K-12 scholars reached in this period. It is evident the quantitative impact of 48 college students reaching out directly over 500 K-12 scholars and over 170 through social media. Table 5 illustrates some examples of major take away reported by students. In addition, our department has established the "Outreach Day" event to celebrate the commitment in reaching out K-12 scholars to promote STEM careers. Students display their projects with a 5-minute presentation and poster. Representatives from many university offices engaged in community service are invited to participate as judges. In addition, representatives from local industries also serving nearby communities with outreach projects are invited to judge the projects and to explore potential industry-academia collaborations in this area. It is a joyous and effective gathering to share initiatives and responsibilities in caring for our communities and the next generation of students, targeting the increased demand for engineering education.

Table 4. Outreach projects for the last edition of the course (Spring 2022)

Communication	Content	Audience	Scholars
Presentation	Chemical engineering and chemistry	High School	20
Presentation	Engineering is for everyone: communication in STEM	High School	35
Hands-on experiment	Raining rainbow	Science fair	300+
Presentation and social media posts	What is a chemical engineer	High School Instagram	20 179
Presentation	Operation Outreach: Our Chemical Engineering Experience	High School	30
Presentation	Chemistry vs Chemical Engineering	High School	18
Presentation	Do you want to be a chemical engineer?	High School	60
Virtual presentation and videos	In my element: becoming an engineer	High School	60

Table 5. A sample of major take away reported by students.

Unique opportunity to go beyond the exclusive technical content of the courses
Convenience for their group age to bring the motivation for STEM careers to K-12 due to proximity in generation sequence
The realization that junior and senior high school students value very much the direct information from college students and the opportunity to ask questions about their future career
The perception that their message delivered through this project is more impactful for undecided high school students in deciding their college options than the independent research they frequently do, based on their own experience
Tackling misconceptions about chemical engineering career and job popular among high school students, that they also faced before entering college
The added-value experience of mentorship addressing the responsibility of community service as integral part of college education
The eagerness, support, and appreciation of teachers in K-12 programs to bring this type of activities to their classrooms
Great opportunity to introduce the priority of Safety among high school students facing the popular misconceptions of risky exposure and accidents handling at chemical plants
Critical review of teamwork skills (planning, handling deadlines, conflicts resolution, changing dynamics, project management)
Promising and enthusiastic use of social media to deliver their message and to get in contact with high school students choosing their careers

However, senior students taking this course are also in need of advice as they are ready to take their first job or move into grad school. To address this issue, the course provides them with the opportunity to meet and follow up during the semester with alumni from our department. The Legacy project (8% of the final grade) is an academic space where every student in the course is matched by the instructor with one alumna/us to exchange on in-person or virtual conversations about career development and job or academic experience. The project is supported by the office of alumni engagement at university level, profiting from their advice and database. Alumni range from recent graduates to senior executives and retired employees or entrepreneurs. They also include professionals with experience in non-chemical engineering careers (i.e., medicine, law, business, and sports). Students are requested to take the initiative to contact their partners, upon an introduction by the instructor. Students prepare a short bio-sketch (about 2 pp.) of their partners based on profile search and conversations in the first 2-4 weeks of the course. It is intended for students to get an appreciation of successes in personal and professional development of former students.

After that initial approach, students and alumni are free to engage in discussing any topic of mutual interest. However students are asked to produce a short essay (about 2 pp.) on recommendations to improve the formation and training at the department, based on discussions with their partners, and initiatives to enrich the role as alumni. They also produce another short critical assessment at the end of the project with significant takeaway and suggestions to improve it. Students participate in brief focus-group meetings in conjunction with the representatives from the office of alumni engagement to socialize the experience and to get insights to improve alumni's connection with the university. As students get advice, mentorship, and networking, alumni get updated and insight information on the department and the career, in a bi-directional set up of communications. Alumni are contacted by the instructor to hear recommendations. Students have shown a strong support for this project to be kept it in the structure of the course and anticipating their will to play the role of alumni after graduation. Alumni have been a tremendous source of inspiration for students and confirming their willingness to keep participating with new cohorts of students.

A distinctive feature of the course is the emphasis on teamwork and collaboration skills. Students arrive at this course with long experience of team projects close to 1,000 hours. A survey taken at the beginning of the course shows that they consider teamwork skills to be the most relevant learning in their career. However, they have received very limited training in teamwork, generally less than 10 hours' investment in some lectures and introduction to team projects, most during the first year. Observation by instructors generally point towards critical weakness like lack of planning, unclear goals, lack of tracking deadlines and progress, unbalanced work distribution, last minute dedication, lack of motivation, split of task assignments with very reduced synergies, lack of strategies for conflict resolutions, among others.

In addition to some lectures on teamwork, collaboration, and leadership, this course makes use of MS TEAMS to simulate a virtual office where every team has a private space, shared with the instructor to work out the deliverables of the project following some recommended practices to improve teamwork performance. Every team starts with a consensus on a team contract including name, brand, mission statement, vision statement, commitments on work ethic and conflict resolutions. This document covers all the activities for the course.

Every project (i.e., design project, outreach project) must be supported with a plan including goals, deliverables, deadlines, responsibilities, and leadership. It is recommended to update the plan with quantitative assessments on the progress of activities every 3-4 weeks. The plan is accompanied by a logbook where students are invited to post brief notes every week on their contributions. Team activities like meetings or presentations are also to be included. They are advised to record "no-activity" statements when appropriate.

Every 3-4 weeks students are requested to provide anonymous quantitative and qualitative assessment on teammates' performance. By the end of the semester, students produced a final peer-grading evaluation (2% of the final grade), a critical assessment (3% of final grade) with encompassing evaluation of individual and team performance, and the instructor provides a project management evaluation (3% of final grade). The instructor plays a "coaching role" during the course introducing suggestions, reminders, inspirational advice, etc. A detailed evaluation of this approach is still in progress; however it has been first-hand evident that some students benefit and appreciate this scaffold structure while others show some resistance to the routines embedded in this strategy.

Finally, this course is used in the department to provide evidence on ABET criteria 3 student outcomes 2, 3, 4, 5, and 7. The changes introduced in the course to improve it with broader impacts have been mainly driven to better implement ABET student outcomes 2, 3, 4, and 5. The efforts have been rewarded with general students' appreciation of an enriched education and training. However, some students have also showed criticism on the extended content and demands for the course, generally conflicting with job search, interviews, and graduation. Further work is needed to balance the effectiveness of these changes in the time frame of the curricula.

Conclusions

The capstone course on process design for chemical engineering undergraduates provides excellent opportunities for faculty and students to engage in learning dynamics to recap on the main contents from previous courses in the career and to prepare for immediate start of industrial jobs or further proceed in grad school. The core of these courses generally relies on the design of a commercial size plant, involving somewhat all the disciplines in chemical engineering and providing a broad overview of applications, from equipment specifications to economic analysis. However, essential components of chemical engineers' training and performance go beyond the technical content of the required courses. The improvements reported here address such components like consideration of public health, safety, welfare, and social, environmental, and cultural impacts, global awareness, community service, mentorship and networking, and extensive teamwork and collaboration skill development.

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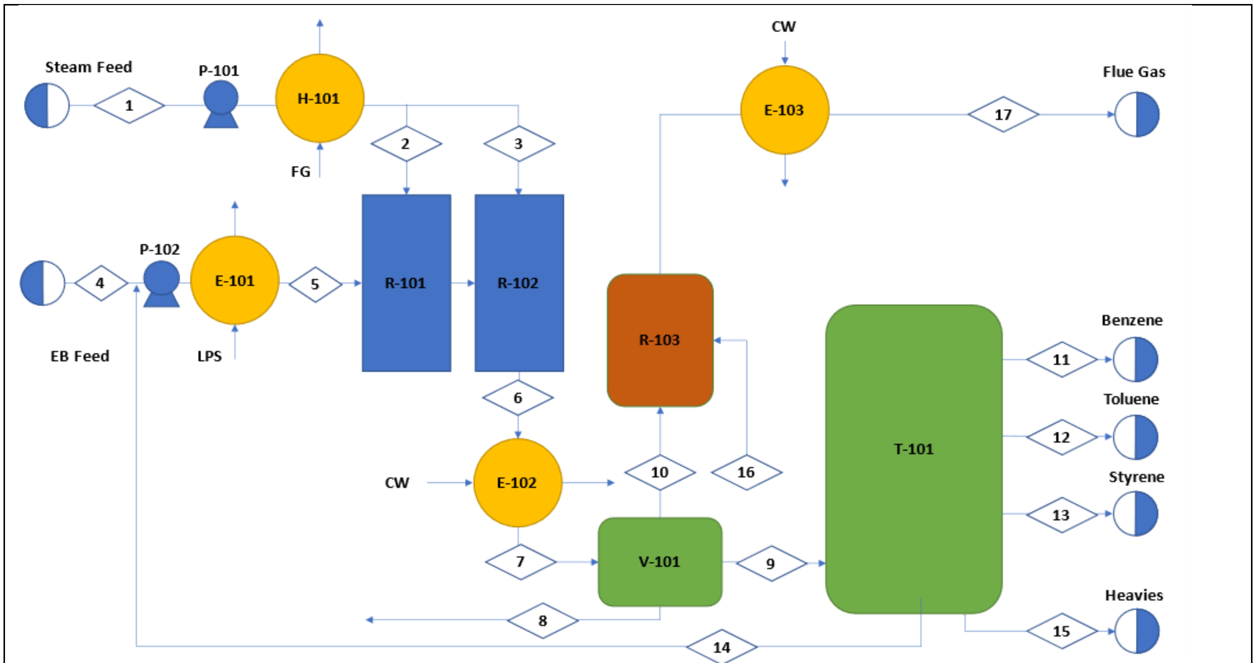
Appendix 1. Illustrative information on results from the technical reports on the project design



Stream	1	2	3	4	5	6	7	8	9
Description	Steam Feed	Heated Steam R1 Feed	Heated Steam R2 Feed	Fresh EB Feed	EB R1 Feed	Products leaving R2	Condensed Products	Water discharge	Oil
Temperature (°F)	70	1425	1425	965	1175	1102		50	<176.18
Pressure (psia)	14.7	26	26	26	26	26		14.7	
Vapor Fraction	0.00	1.00	1.00	1.00	1.00	1.00	0.44	0.00	0.00
lb/hr	1.35 E5	6.58 E4	6.94 E4	3.68 E4	6.47 E4	2.00 E5	2.00 E5	1.34 E5	6.28 E4
g-mol/hr (300 days 24hr/day)	3.40 E6	1.66 E6	1.75 E6	1.57 E5	2.76 E5	3.86 E6	3.86 E6	3.36 E6	2.74 E5
lbmol/hr	7505.07	3655.07	3850.00	346.90	609.18	8502.05	8502.05	7413.64	604.37
Stream	10				11	12	13	14	
Description	H2	CH4	Ethylene	CO2	Benzene	Toluene	Styrene	EB Recycle	
Temperature (°F)									
Pressure (psia)	14.7				14.7	14.7	0.580	0.580 or 14.7	
Vapor Fraction	1.00	1.00	1.00	1.00	1.00	1.00	0.00	0.00	
lb/hr	815.77	308.77	404.97	2012.08	1503.62	2881.95	2.99 E4	2.78 E4	
g-mol/hr (300 days 24hr/day)	1.84 E5	8731.66	6548.75	2.07 E4	8731.66	1.42 E4	1.30 E5	1.19 E5	
lbmol/hr	404.65	19.25	14.44	45.72	19.25	31.28	286.74	262.28	
Stream	15		16		17				
Description	Naphthalene	Ethylnaphthalene	Air - O2	Air - N2	Stack Gas CO2	Stack Gas H2O	Stack Gas Unreacted O2	Stack Gas Unreacted N2	
Temperature (°F)			70		>250				
Pressure (psia)	0.580		14.7		14.7				
Vapor Fraction	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	
lb/hr	308.39	375.92	1.14 E4	3.74 E4	4130.07	8503.94	2273.09	3.74 E4	
g-mol/hr (300 days 24hr/day)	1091.46	1091.46	1.61 E5	6.06 E5	4.26 E4	2.14 E5	3.22 E4	6.06 E5	
lbmol/hr	2.41	2.41	355.17	1336.11	93.84	472.02	71.03	1336.11	

Figure A1. Illustrative information on preliminary process flow diagram (PFD) and mass balance

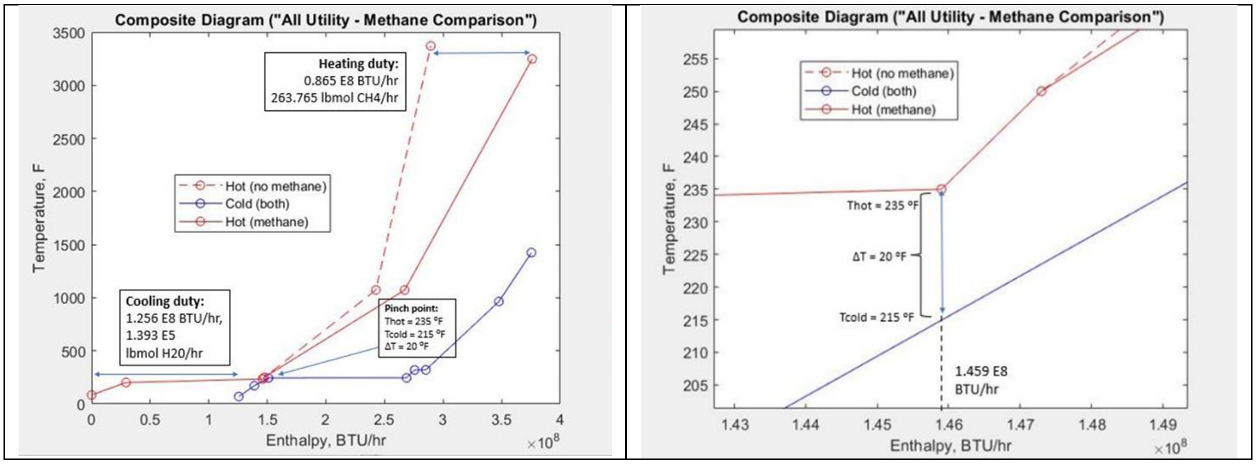


Figure A2. Illustrative information on Pinch Analysis calculations (Graphical method)

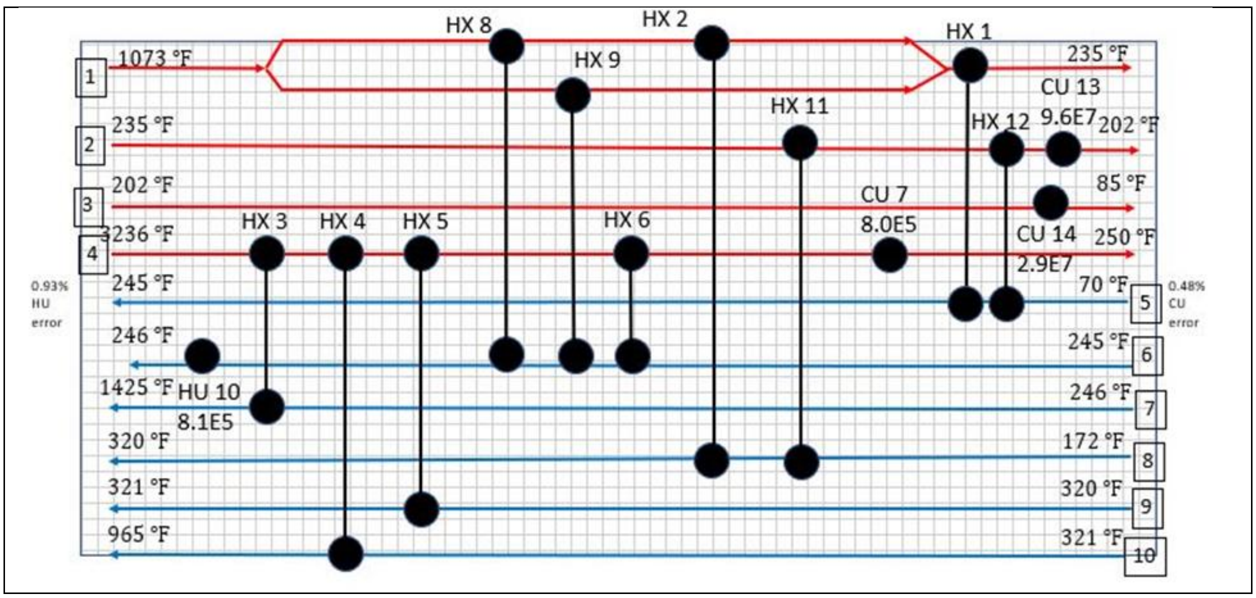


Figure A3. Illustrative information on Heat Exchanger Network analysis

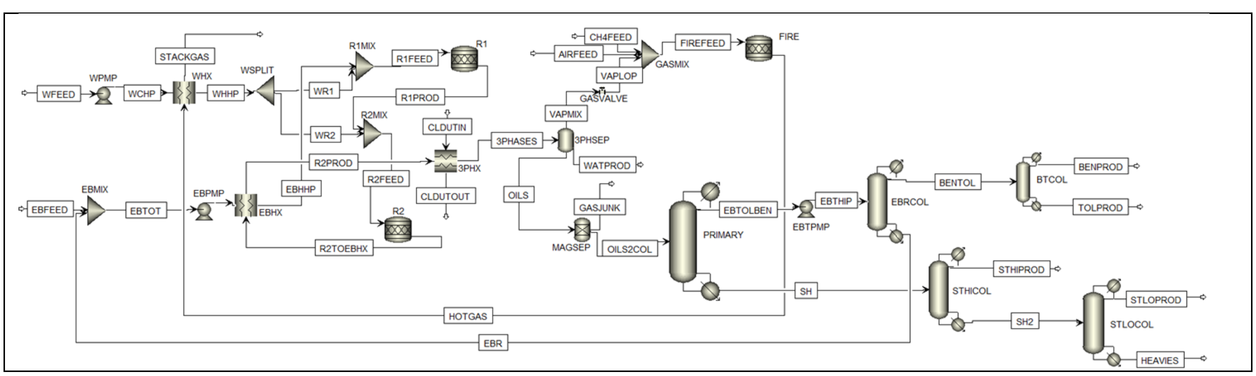


Figure A4. Illustrative information on ASPEN basic model for the plant

Figure A5. Illustrative information on ASPEN based pinch analysis of steam generator (top) and feedstock heater (bottom)

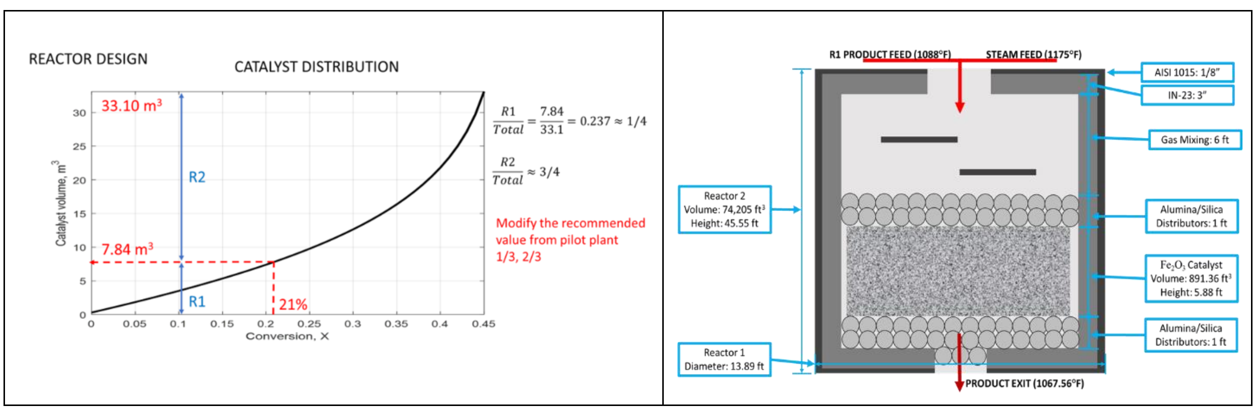


Figure A6. Partial information on elements for the reactor design

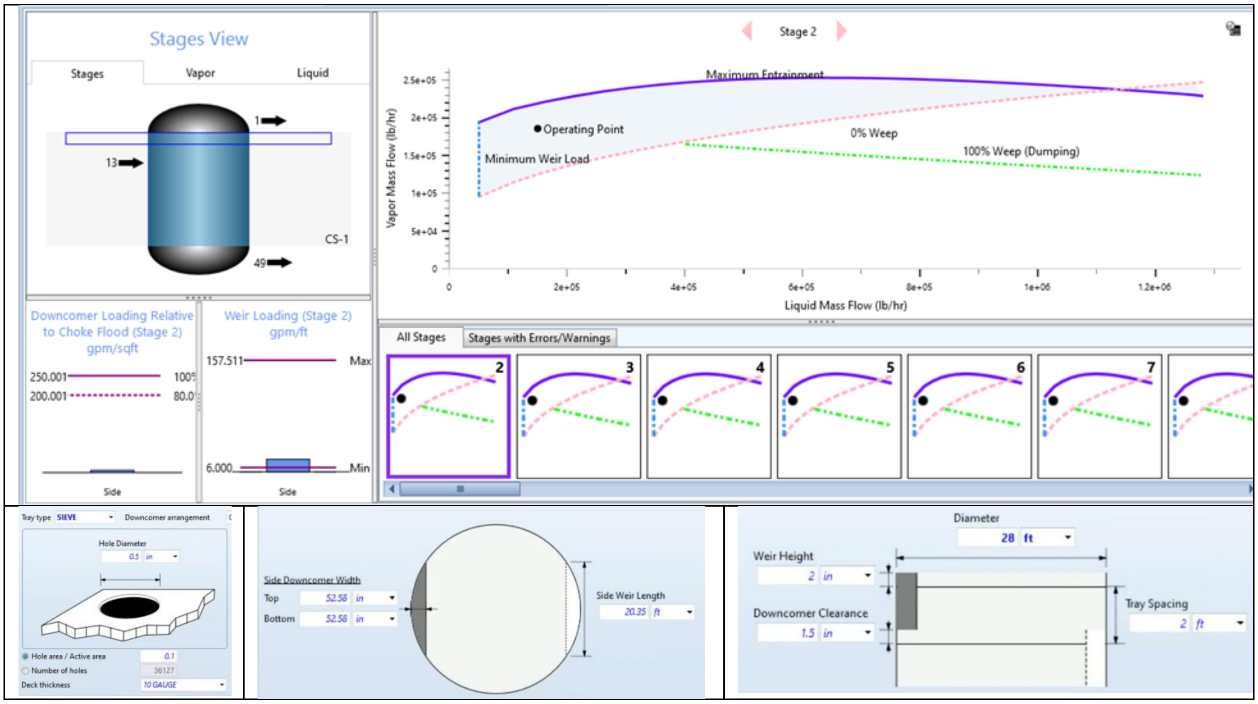


Figure A7. Illustrative information on distillation column hydraulics and internals

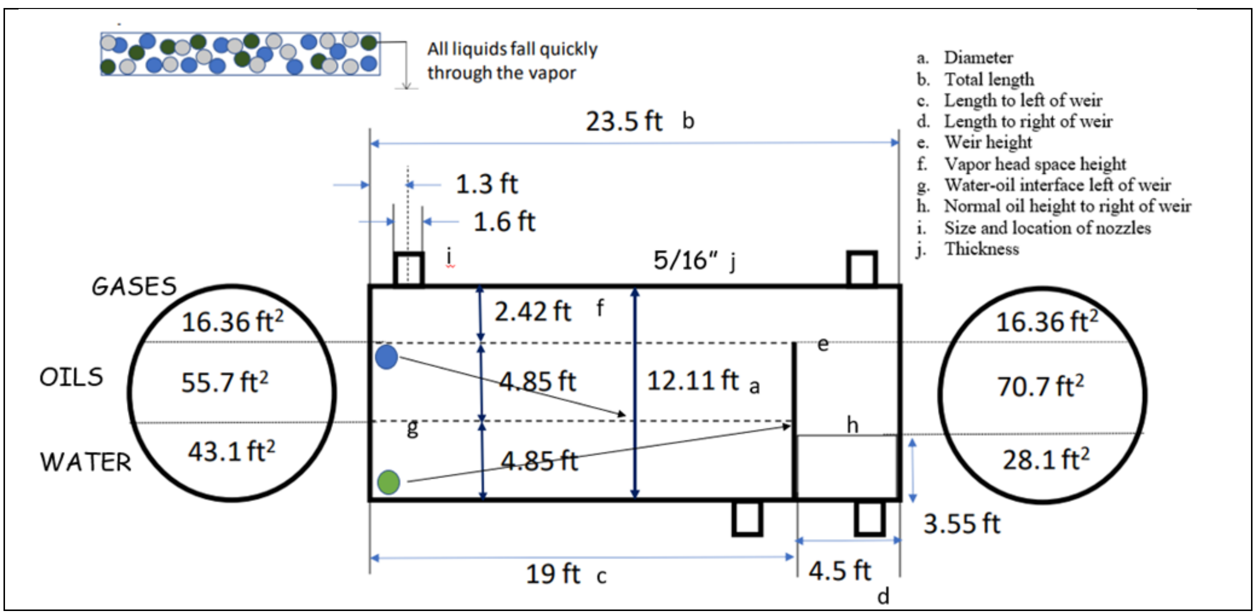


Figure A8. Illustrative information on a three-phase separator sizing (normal operation)

Heat Exchanger Specification Sheet

#						
1	Company: University of Pittsburgh					
2	Location: Swanson School of Engineering					
3	Service of Unit:	Our Reference:				
4	Item No.:	Your Reference:				
5	Date:	Rev No.:	Job No.:			
6	Size : 49 - 120 in	Type: BEM Horizontal		Connected in: 1 parallel	1 series	
7	Surf/unit(eff.) 4146.9 ft^2	Shells/unit 1		Surf/shell(eff.)	4146.9 ft^2	
8	PERFORMANCE OF ONE UNIT					
9	Fluid allocation		Shell Side		Tube Side	
10	Fluid name		EBHHP		R2PROD	
11	Fluid quantity, Total	lb/h	68359.9		187963	
12	Vapor (In/Out)	lb/h	0	68359.9	187963	187963
13	Liquid	lb/h	68359.9	0	0	0
14	Noncondensable	lb/h	0	0	0	0
15						
16	Temperature (In/Out)	°F	172.12	964.65	1073.3	703.81
17	Bubble / Dew point	°F	318.89 / 319.07	312.34 / 312.51	/	/
18	Density Vapor/Liquid	lb/ft^3	/ 51.094	0.166 /	0.039 /	0.046 /
19	Viscosity	cp	/ 0.3676	0.0158 /	0.0301 /	0.0226 /
20	Molecular wt, Vap			106.07	24.5	24.5
21	Molecular wt, NC					
22	Specific heat	BTU/(lb-F)	/ 0.4392	0.6284 /	0.5719 /	0.5194 /
23	Thermal conductivity	BTU/(ft-h-F)	/ 0.067	0.038 /	0.049 /	0.034 /
24	Latent heat	BTU/lb	139.4	140.4		
25	Pressure (abs)	psi	26	23.79	26	23.25
26	Velocity (Mean/Max)	ft/s	26.84 / 67.35		288.3 / 314.3	
27	Pressure drop, allow./calc.	psi	5	2.21	5	2.75
28	Fouling resistance (min)	ft^2-h-F/BTU	0.0005		0.0005	0.0006 Ao based

#						
29	Heat exchanged	37924760	BTU/h	MTD (corrected)	304.12	°F
30	Transfer rate, Service	30.07	Dirty 35.62	Clean 37.13	BTU/(h-ft^2-F)	
31	CONSTRUCTION OF ONE SHELL				Sketch	
32				Shell Side	Tube Side	
33	Design/Vacuum/test pressure		psi	50 / /	50 / /	
34	Design temperature / MDMT		°F	1140 /	1140 /	
35	Number passes per shell			1	1	
36	Corrosion allowance		in	0.125	0.125	
37	Connections	In	in	1 3.5 / -	1 30 / -	
38	Size/Rating	Out		1 14 / -	1 30 / -	
39	Nominal	Intermediate		/ -	/ -	
40	Tube #: 2304	OD: 0.75	Tks. Average 0.083 in	Length: 120 in	Pitch: 0.9375 in	Tube pattern: 30
41	Tube type: Plain	Insert: None		Fin#: #/in	Material: Carbon Steel	
42	Shell Carbon Steel	ID 49	OD 50.375 in	Shell cover	-	
43	Channel or bonnet	Carbon Steel		Channel cover	-	
44	Tubesheet-stationary	Carbon Steel	-	Tubesheet-floating	-	
45	Floating head cover	-		Impingement protection	None	
46	Baffle-cross Carbon Steel	Type Single segmental	Cut(%d) 40.06	Ve Spacing: c/c 22	in	
47	Baffle-long -	Seal Type		Inlet 22	in	
48	Supports-tube	U-bend 0		Type		
49	Bypass seal		Tube-tubesheet joint	Expanded only (2 grooves)(App.A 'i')		
50	Expansion joint	-	Type None			
51	RhoV2-Inlet nozzle 1497	Bundle entrance 31		Bundle exit 1834	lb/(ft-s^2)	
52	Gaskets - Shell side	-	Tube side	Flat Metal Jacket Fibe		
53	Floating head	-				
54	Code requirements	ASME Code Sec VIII Div 1	TEMA class	R - refinery service		
55	Weight/Shell	27546.1	Filled with water 41509.8	Bundle 17599.8	lb	
56	Remarks	EBHX				
57	CHE0613					
58						

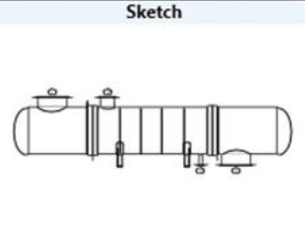


Figure A9. Illustrative information on heat exchanger specification sheet

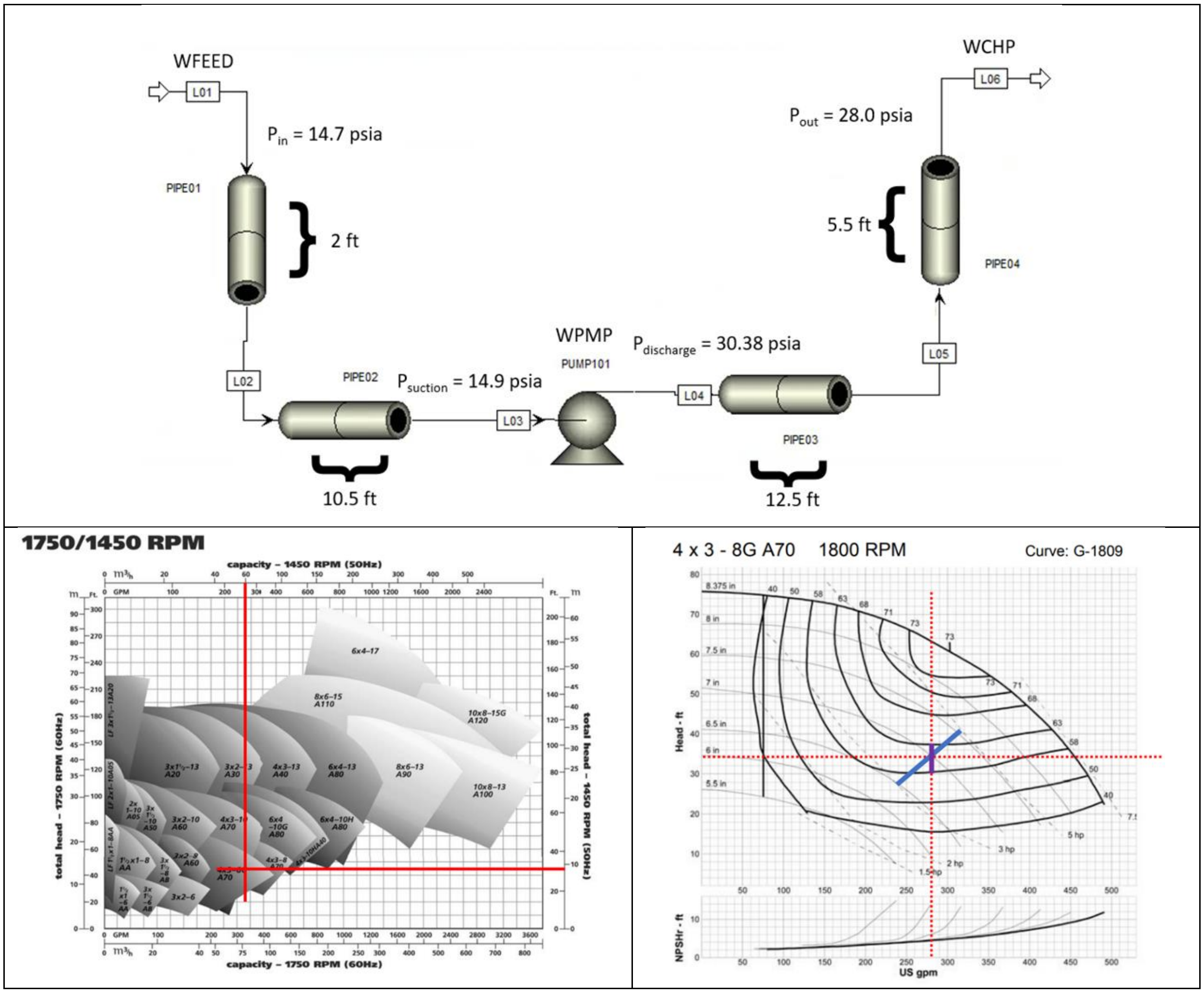


Figure A10. Illustrative information on pump sizing and selection

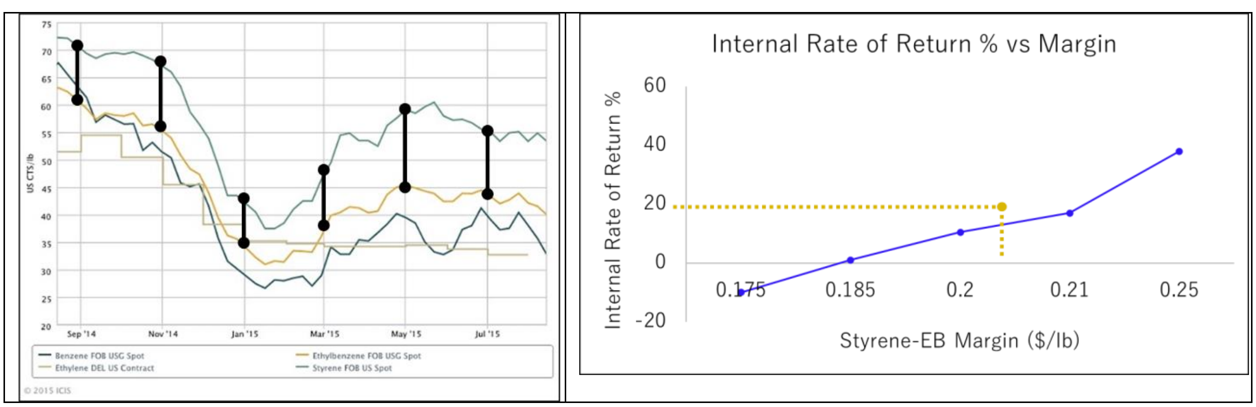


Figure A11. Illustrative information on price margin and profitability analysis

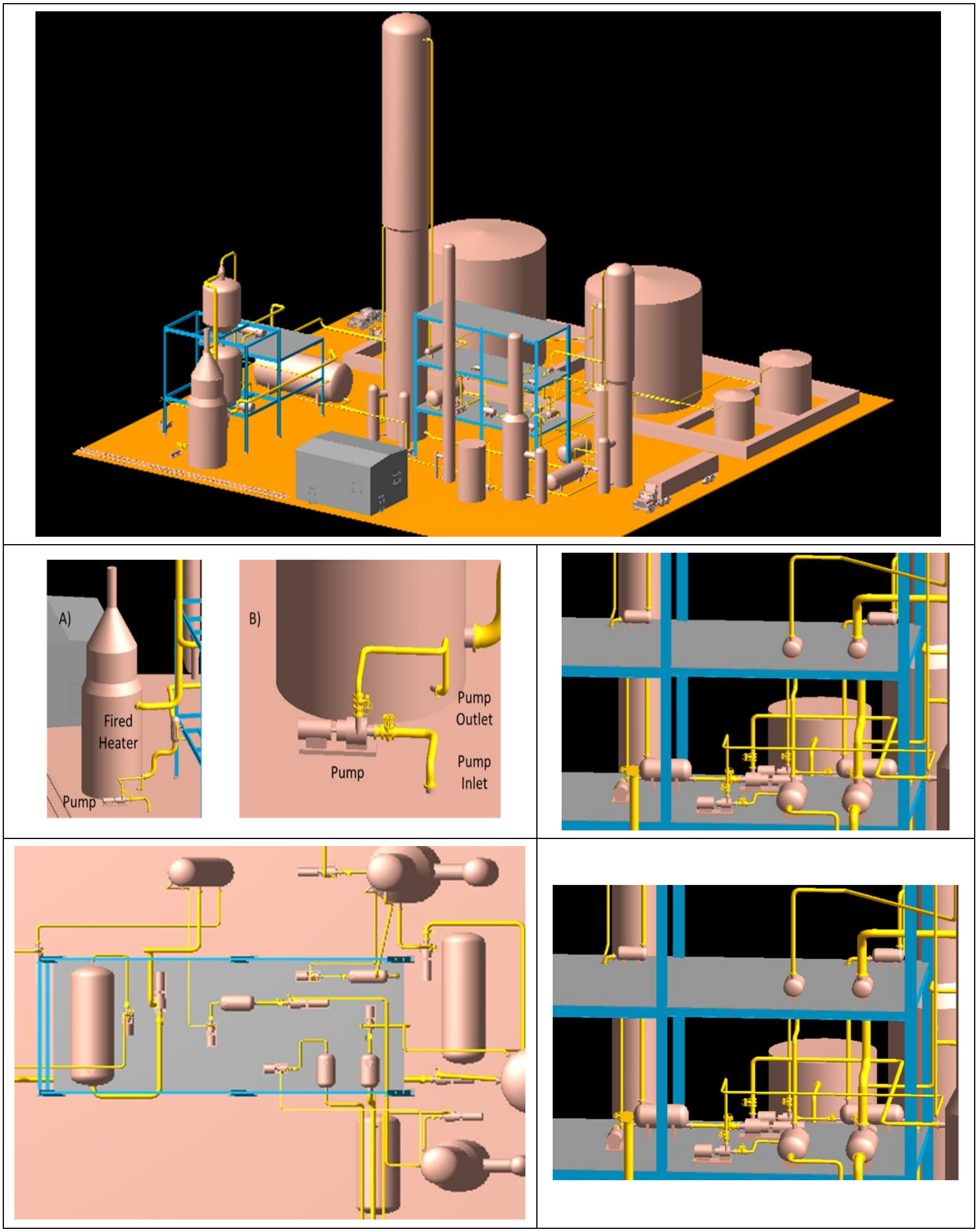


Figure A12. Illustrative information on 3D simulation of the plant by AVEVA software

Appendix 2. Rubric for the final presentation of the project

DESIGN PROJECT PRESENTATION EVALUATION

Term

Team Name ______________________________ Evaluator ________________

Topic (Weight)	**Unacceptable (0)**	**Marginal (1)**	**Acceptable (2)**	**Exceptional (3)**	**Points**
Product Demand and Raw Materials Availability and Pricing (2)	Little or no understanding of the market. Incapable of producing a profitable product.	Some understanding of the market. Major deficiencies that will affect the ability to produce a profitable product.	Overall sound understanding of the market. Does not significantly impair solution.	Clear and thorough understanding of market and ability to produce a profit.	
Process Flow Diagram (3)	Process flow diagram is clearly infeasible.	Some deficiencies in process flow diagram.	Process flow diagram meets desired objectives.	The final process flow diagram clearly meets or exceeds desired objectives.	
Material and Energy Balances (3)	Erroneous material and energy balances.	Some deficiencies in the completion of the material and energy balances.	Adequate completion of material and energy balances.	Clear and concise completion of material and energy balances.	
Design and Cost of Major Pieces of Equipment (5)	Erroneous design and/or costing of major pieces of equipment.	Some deficiencies in proper design and costing of major equipment.	Effective design and costing of major equipment.	Critical design and costing of major equipment ensuring reasonable results.	
Process Optimization/Energy Conservation (3)	Erroneous results provided by process optimization / energy conservation.	Some deficiencies provided by process optimization / energy conservation.	Process optimization / energy conservation meets desired objectives.	Process optimization / energy conservation meets or exceeds desired objectives.	
Process Control Scheme/Controllers (2)	Erroneous design of process control scheme.	Some deficiencies in the design of the process control scheme.	Process control scheme meets desired objectives.	Process control scheme meets or exceeds desired objectives.	
Process Safety and Design Concerns (2)	Little or no understanding of process safety and design concerns.	Some understanding of process safety and design concerns.	Overall sound understanding of process safety and design concerns.	Clear and thorough understanding of process safety and design concerns.	
Process Environmental Considerations / Sustainability / Green Energy Tech (2)	Little or no understanding of process environmental considerations / sustainability / green energy technologies.	Some understanding of process environmental considerations / sustainability / green energy technologies.	Overall sound understanding of process environmental considerations / sustainability / green energy technologies.	Clear and thorough understanding or process environmental considerations / sustainability / green energy technologies.	
Process Economics (3)	Erroneous economic conclusions based on proposed design.	Some deficiencies in economic conclusions.	Sound conclusions reached based on economic evaluation.	Insightful, supported economic conclusions and recommendations.	
Team Participation (2)	Not all team members participated in the presentation / explanations / questions.	Most team members participated but without evidence of adherence to teamwork.	Participation of all team members, but with little evidence of teamwork.	Participation by all team members with evidence of advanced teamwork.	
Presentation Format (10 min) (3)	Not within time limit, ineffective use of visual aids, little use of correct technical language.	Not within time limit, ineffective use of visual aids, little use of correct technical language.	Within time limit, ineffective use of visual aids, appropriate technical language.	Within time limit, effective use of visual aids, appropriate technical language.	
Questions and Answers (5 min) (3)	Serious deficiencies in understanding and answering questions.	Some understanding of questions and answers.	Effective understanding of questions and answers, but only by some team members.	Effective understanding and answering of questions by all team members.	
POINTS	**0–50**	**51-69**	**70–84**	**85–99**	