Development of A SYSTEMS ENGINEERING UNDERGRADUATE ELECTIVE FOR CHEMICAL ENGINEERING STUDENTS

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Systems engineering concepts are frequently applied to government procurement efforts to ensure effective technical leadership for projects that require the interaction of many complex components.[1–3] The role of the systems engineer is shown in Figure 1, which identifies both systems engineering and project control as the two key areas of project management. As shown in the figure, the systems engineer is more focused on leading the system design than on the financial aspects of the project. Systems engineering methods ensure the successful integration of many smaller systems into one complete design, and the methods become more valuable as program complexity and costs increase.[4-6]

The importance of systems engineering is articulated by the National Society of Professional Engineers, which states that an engineer entering practice at the professional level should have a knowledge of the basics of systems engineering.[7] As a result, formal degree programs are now offered at the undergraduate and graduate level.[8-11] However, traditional mechanical, chemical, and electrical engineering degree programs do not typically include systems engineering concepts as degree requirements. Yet, many students will find that technical project leadership skills are required for many of the projects in the workforce. Thus, a need exists to educate students about systems engineering and the procurement of complex technology.

To address this need, the Department of Chemical and Biomolecular Engineering at the University of South Alabama offered a one-semester, 3-credit hour, systems engineering elective for chemical engineering seniors for four years.

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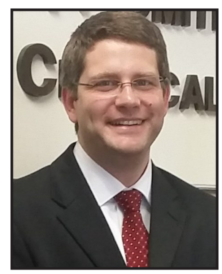

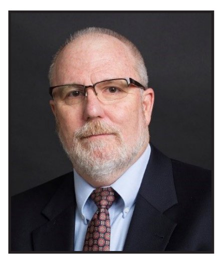

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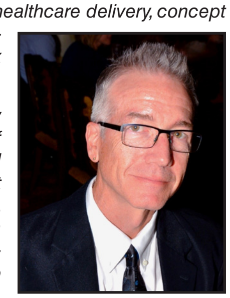

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In the class approximately 15-20 students would design an engineering apparatus in the Fall, and then a selection of approximately five students would build the apparatus in the Spring as their Capstone Design Project.

In three out of the four years this class was offered, the project was funded by the NASA's eXploration Habitat (X-Hab) Academic Innovation Challenge and the National Space Grant Foundation.[12] A full description of the program, the design project problem statements, and the design constraints are provided on the X-Hab website.[13] In the Fall of 2017, the course was taught without external funding, and the students used systems engineering techniques to design Unit Operations Lab equipment. This manuscript discusses the structure of the elective course, the types of systems produced, and the lessons learned.

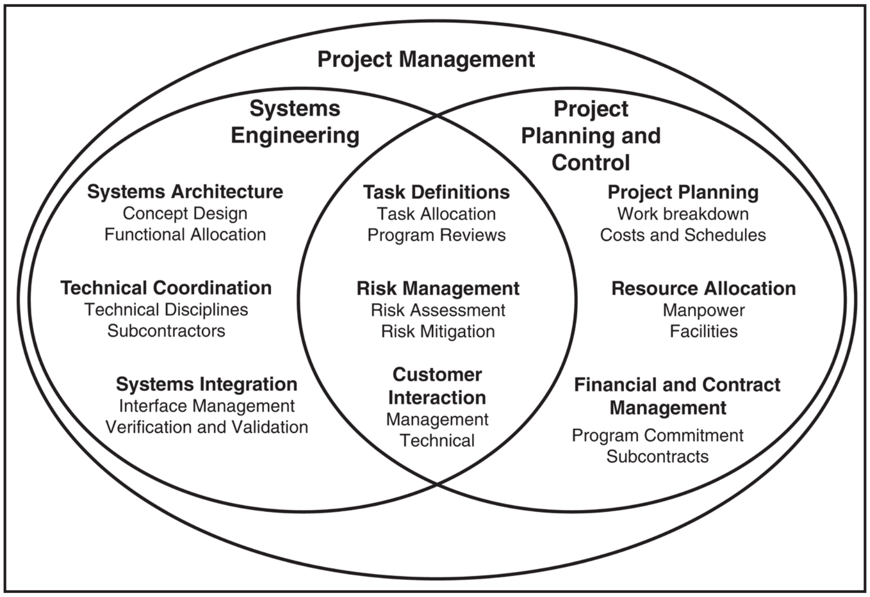

Figure 1. *The distinction between systems engineering and project management.[15] Used with permission from Wiley 2011.*

STRUCTURE OF THE X-HAB ELECTIVE COURSE

Research suggests that project-based learning improves student retention, satisfaction, diversity, and learning.[14,15] Therefore, the course included a project component where students applied systems engineering techniques, along with a classroom component with assigned readings, short quizzes, and brief lectures introducing systems concepts. The project was the centerpiece of the course.

The textbook *Systems Engineering Principles and Practice* was used because it provides a broad introduction to systems engineering concepts[16]; however, other sources could have also been used.[2,17] Table 1 outlines the topics that were covered during the course. The time committed to each topic in Table 1 varied to ensure balance between the project and lecture portions of the course based on the complexity of the given project. The topics were selected to ensure that students had enough exposure to systems engineering so that they could begin work on the class project early in the semester.

After providing context for the need of systems engineering skills, the class discussed the first steps in the development of a new system. Specifically, the class covered completing a needs analysis, concept exploration, concept definitions, requirements analysis, and trade off analysis. Finally, over the remaining portion of the semester, the students learned specific systems engineering concepts including the system life cycle, the systems engineering method, a work-breakdown-structure (WBS), a systems engineering management plan (SEMP), test and evaluation management plan (TEMP), and systems engineering methods to manage risk. These terms may be unfamiliar to chemical engineers, and a full description of each is outside the scope of this manuscript. Fortunately descriptions of each term are readily available elsewhere.[1-3,17]

Students understand the concept exploration phase from previous engineering projects; however, most students have no experience completing a requirements analysis and examining how requirements impact project design. Given the number of students participating in the class, and with each presenting different design alternatives, the students quickly realized how formalizing project requirements helps a design stay focused on project objectives. In many cases, students with prior work experience quickly recognized the value of having a set of methods specifically devoted to managing complex projects.

Structure of the X-Hab Systems Engineering Project

Over the one-year period of performance of the X-Hab project, NASA required that the students complete a sequence of program reviews. First, the students completed a systems definition review (SDR), which consists of an initial concept discussion with stakeholders. After the SDR the students completed a preliminary design review (PDR) and, finally, a critical design review (CDR) where nearly everything is specified in the system design. For more complex programs each of these reviews has specific entrance and exit criteria that must be satisfied. The *NASA Systems Engineering Handbook* lists these items and provides an excellent resource for supervising the design of complex projects.[17] The program reviews were provided via a teleconference or via a web-based desktop sharing program. Specifically, the students developed a slide set showing the work-breakdown structure, and detailed how the system was divided into subsystems, components, and parts. Additionally, the students quantified project risk in terms of project impact and the likelihood of the event occurring.

TABLE 1
Topics covered in lecture

What is Systems Engineering	
	broad intro topics in systems engineering
	needs analysis
	metrics and testing
	trade-off analysis
	interfaces
	requirements
	risk
	multidisciplinary project leadership
System Engineering Approaches	
	program management, control, and systems
	definition of a life cycle
	systems engineering diagrams
	system engineering design balance
System Environment and Boundaries	
	context diagrams
	definition of boundaries
	interfaces
	systems of systems concept
Concept Exploration	
	systems engineering method
	requirements
	functional analysis
	physical definition
	design validation
	unknowns
	system architecture
System Review	
	kick-off meeting
	preliminary design review
	critical design review
	presentation development
	work breakdown structure
Software Systems	
	integration of software and hardware in design
	interfaces
	software development life cycles
Test and Evaluation	
	why test and evaluation plans matter
	test and evaluation plan development
	test and evaluation plan review

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The students also developed a project budget estimate and a Gantt chart. The faculty member ensured that key elements of the NASA systems method were maintained and matched the systems effort to the complexity of the system produced.

These presentations were provided to NASA subject matter experts (SMEs) with expertise related to the specific project being built. This provided the students with not only a sounding board for ideas, but also a set of experts that asked challenging and open-ended questions to the students.

Each year, only one student served as the lead systems engineer and three to four additional students were placed in charge of different subsystems of the project. Lead roles were determined by student interest and motivation, and students in lead roles delegated supporting tasks to the remaining students in the class.

With each project, electrical and mechanical engineering students from other departments participated as paid subcontractors. This served a dual purpose: (1) X-Hab students could quickly and efficiently utilize the skills of others outside their area of engineering knowledge; and (2) this enhanced the class' experience to more closely resemble a project within an industrial setting. At the direction of the X-Hab students, the student subcontractors developed a 3D computer-aided drawing (CAD) of each system and developed the LabVIEW interface. The X-Hab students developed a statement of work for each subcontractor detailing the work that was required, the type of deliverable that was expected, when the work must be completed, and how much the contractor was paid. In some chemistry and engineering curriculums LabVIEW as a data acquisition and control tool is taught in lab classes and, in these cases, the students may be sufficiently proficient programmers to provide a LabVIEW interface without paying a student contractor.[18–22]

Each X-Hab period of performance was one year and each project ran during both the Fall and Spring semesters. During

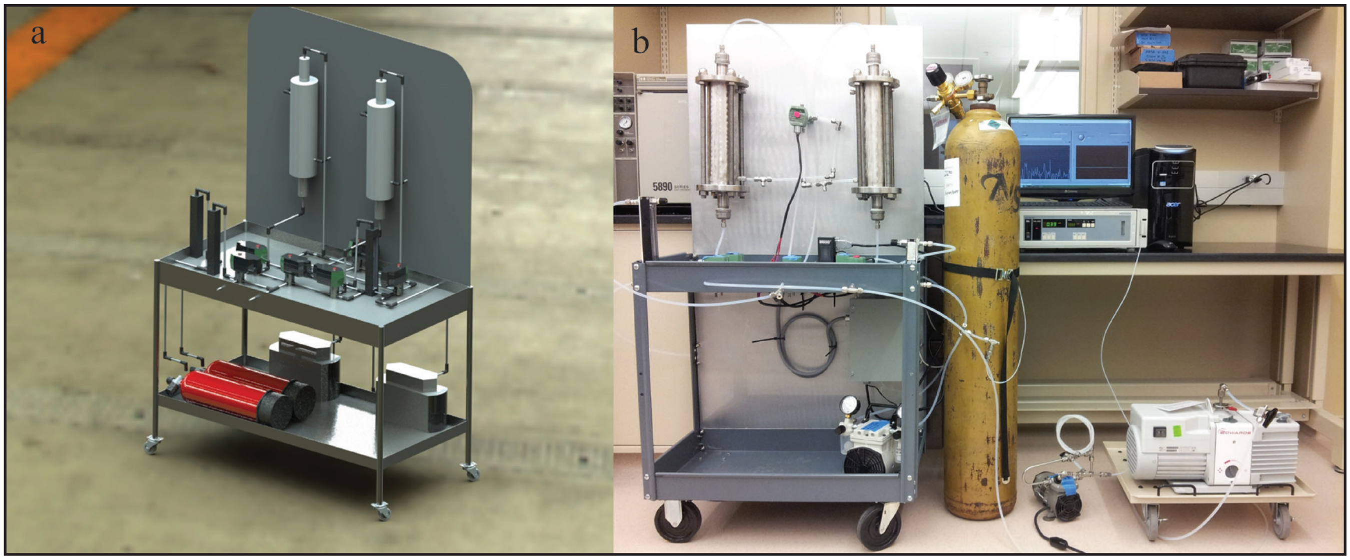


Figure 2. *Vacuum swing adsorption system built by undergraduates using systems engineering methods: (a) computer aiding drawing of the system to be built; (b) the completed vacuum swing adsorption system.*

the Fall semester, the students completed a detailed design of the X-Hab project and ordered all the parts necessary to construct the system. Documentation of the project decisions, parts selection, budget updates, and other tasks ran continuously throughout the project. At the end of the Fall semester the team produced a final report that detailed the design, addressed design rationale and approach, and detailed the remaining tasks that needed to be completed.

In the Spring semester, the lead engineers on the project constructed a working system based on the detailed plan laid out during the Fall semester. The construction of the system served as their Senior Capstone Design Project. Per the requirements for graduation of the Capstone Design Project, the X-Hab students still provided design reports, poster presentations, and written reports based on their X-Hab project.

With this type of project design, it is critical that all the parts are ordered in the Fall semester to ensure a timely assembly in the Spring. Also, because the students were conducting the work in a lab setting, standard university safety policy governed the work of the students. In some of the projects, precision machine shops build customized parts or weld tubing to avoid students operating industrial milling or welding machinery.

Assessment of Student Performance

Grades for the Fall X-Hab elective course were calculated based on two equally weighted parts: (1) the students' performance on the quizzes covering the material from the textbook; and (2) the contributions of the students to the X-Hab project. Individual contributions by the lead engineers were easy to identify as these students presented regular project updates to NASA and selected the parts for procurement. The remaining portion of the class gave oral presentations and wrote reports detailing their contributions to the project in the form of background literature review assignments, discussion about the operation of analytic equipment, or other supporting details. With this approach individual performance and contribution were distinguishable from the group.

During the Spring semester technical presentations and a final written report of the X-Hab team's work were assessed. The students also completed presentations as part of their Capstone Design Course requirements. Specifically, halfway through the Spring semester the X-Hab team leaders presented an update on the project construction to the class and to guest faculty members. Students and guests asked questions at the conclusion of the presentation for the X-Hab team leaders to answer. This process was repeated at the end of the Spring semester after the design was completed. Next, the X-Hab team leaders made and presented a poster at a University Senior Design Symposium. The symposium provides an opportunity for faculty in other departments to examine the capstone projects of the students. Also, engineers working in the local area attended this event and provided technical questions for the students during the oral and poster presentations of the work. Lastly, an engineer that holds a professional engineering license read and graded the written report. Each student's grade was then calculated based on the scores of each of the presentations (four in total not including presentations to NASA) and the written report.

COMPLETED X-HAB PROJECTS

During the 2012/2013 academic year the class produced a vacuum swing adsorption apparatus as shown in Figure 2. The CAD rendering for this figure was detailed and closely resembled the completed system. The students completed a work-breakdown structure, risk analysis, and diagrams detail-

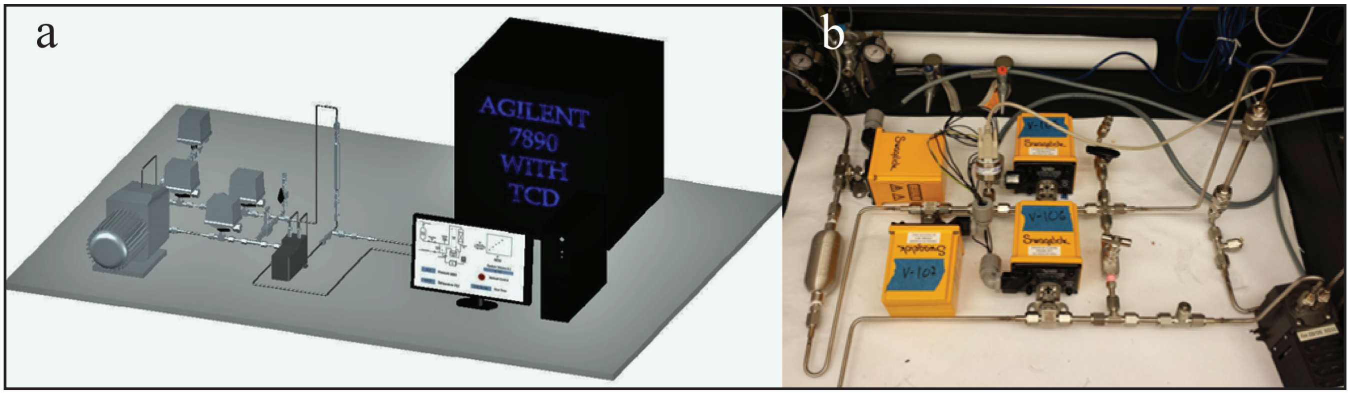


***Figure 3.** Multicomponent volumetric adsorption system built by undergraduates using systems engineering methods: (a) computer aiding drawing of the system to be built; (b) the completed adsorption system.*

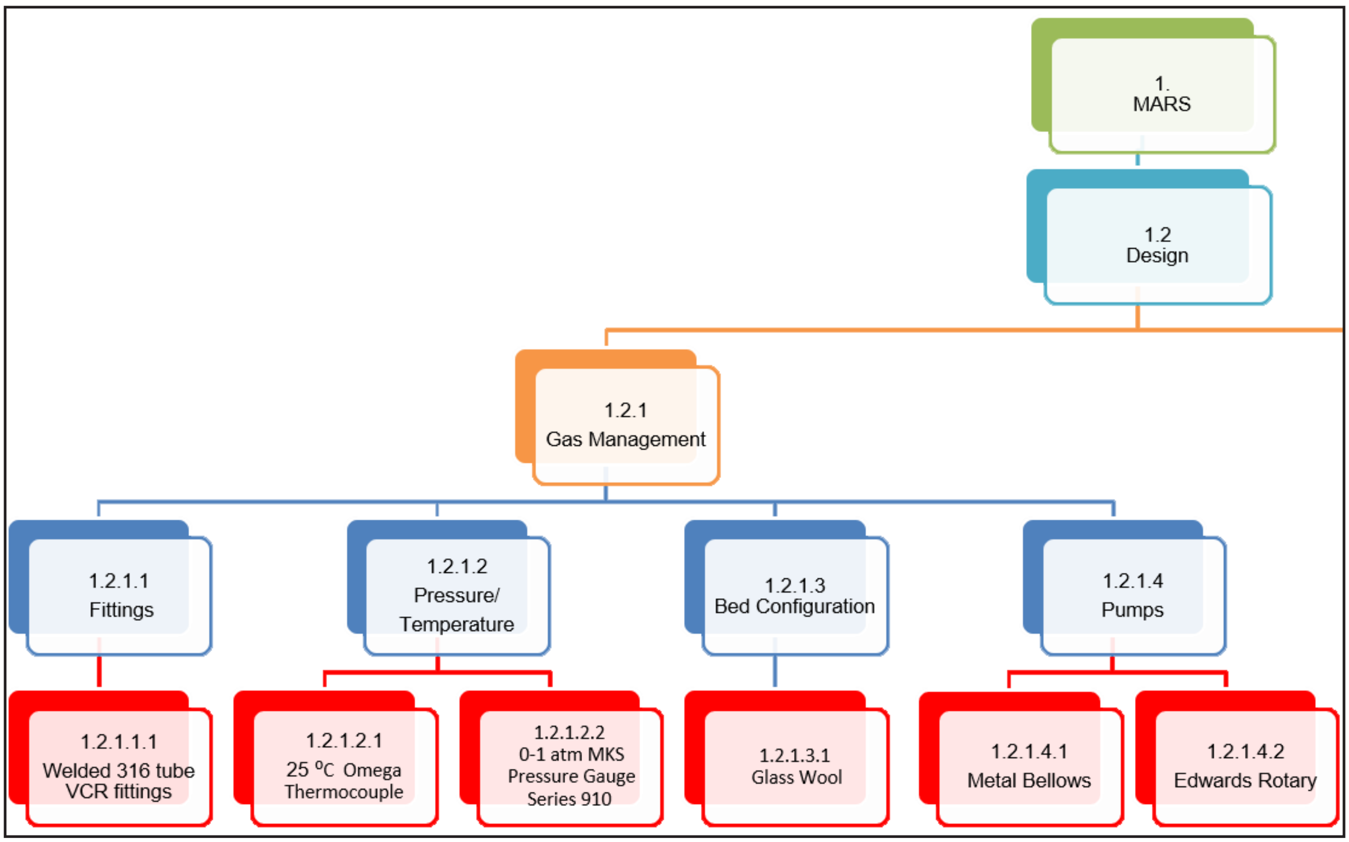


***Figure 4.** A portion of the work-breakdown structure for the "MARS" project shown in Figure 3.*

ing the operation of the system. The students also developed other technical schematics detailing the system including a block flow diagram as well as diagrams showing how the valves would actuate during system operation. When this project was completed the apparatus provided continuous automated operation for 12 hours without user input. Similar projects were completed during the 2013/2014 and 2014/2015 academic years. For example, during the 2013/2014 year the students built a volumetric adsorption apparatus as shown in Figure 3.

A portion of the work-breakdown structure for the volumetric adsorption apparatus is shown in Figure 4. The system was broken down into three primary subsystems: "Gas Management," "Automation and Instrumentation," and "Analytics." Each of these subsystems were further divided into different areas and finally into particular parts. Once the system was decomposed to the parts level of the work breakdown, the students were responsible for obtaining vendor quotes and ordering the parts. For clarity, Figure 4 only shows the "Gas Management" section of the work-breakdown structure.

Likelihood	Impact	Overall	Risk	Priority
5	5	High	Delay in Parts	1
4	5	High	Project goes over schedule	2
3	5	High	GC malfunctioning	3
4	3	Medium	LabVIEW Failure	4
1	4	Medium	System Leak	5
1	3	Low	Insufficient funding	6

(a)

(b)

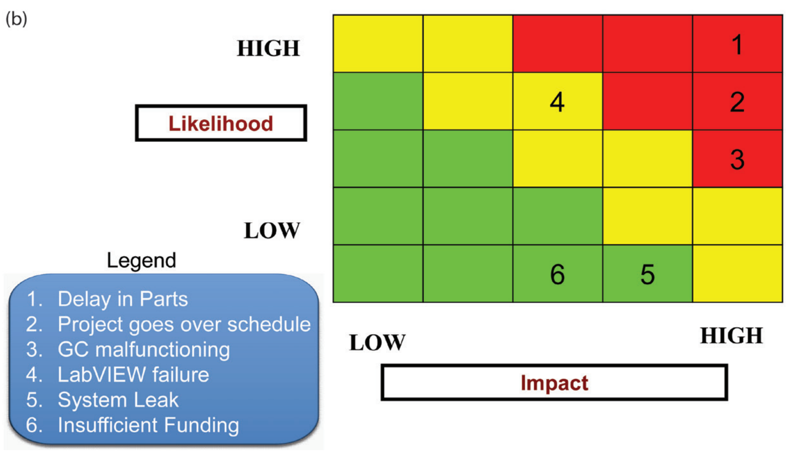


Figure 5. *Student identification of risk for Figure 3 apparatus. (a) List of risks. (b) Graphical presentation of risks.*

Additionally, each year the students completed a risk assessment to identify the most impactful and most likely sources of risk. A risk matrix, as shown in Figure 5, summarized any identified risk of the project and then the students developed risk mitigation strategies.

Systems engineering frequently makes use of diagrams to show inputs, outputs, and enablers that must be considered when a complex system is in operation. These figures are important when building complex systems because they help identify interfaces between sub-systems, which are common points of systems failure. The use of systems engineering diagrams also allows the students to develop the system design abstractly. Specifically, this type of analysis allowed the students to learn a technique where the objective and stakeholder requirements were considered in a design phase without detailing the specific aspects of how that system would complete the work. This logical (or abstract) systems engineering approach prevents the students from adapting a physical architecture too early in the design process that may not effectivity capture all the design requirements. Analogously, when teaching chemical engineering capstone design, it is common to develop chemical-plant designs in different phases of detail to ensure all options are considered and to minimize design costs, which is consistent with a system engineering perspective.

For example, during the 2015/2016 year the students developed a device to measure gas-phase diffusion rates in porous solids. As the students worked through the design process they developed Figure 6 to show all the inputs to the system, constraints and commands provided to the system, a mathematical model required by the system, and expected outputs. Then Figure 7 was developed to show how each of these inputs are managed to produce the expected output. Unlike a chemical engineering block flow diagram that typically details mass and energy, Figure 7 also shows concentration data exiting the measure-components block and moving to a calculations block.

X-Hab Projects Outcomes

Because the X-Hab projects have been incorporated into the Capstone Design sequence, the results are presented by students to the faculty of the department and to the department's industrial advisory board during the Senior Design Symposium. The limited time of the presentation—15 minutes—was a challenge for the students because it was often difficult for them to prioritize the information that needed to be presented. Also, because the symposium audience had a varied technical background, the students had to provide appropriate context for the engineered X-Hab system. Local practicing engineers were pleased to see the students become familiar with system design, budget management, and equipment automation.

Comparison of the X-Hab student projects to the traditional chemical engineering student projects provided insight into why systems engineering methods should be integrated into chemical engineering design curriculums. For example, the documentation associated with the X-Hab student projects was much more likely to discuss program/project objectives, expected outputs/deliverables, and stakeholders than traditional design projects, which were more likely to discuss only the detailed engineering. In many cases, traditional teams envisioned specific hardware first and then completed detailed design of that hardware to satisfy the project expectations. Little if any systems architecting was done during the project to ensure that all possible solutions were considered or to identify unknowns. This type of contrasting approach is consistent with traditional design versus systems-based design. The observation that a traditional student design team completed a design and then documented the results, instead of documenting continuously via systems engineering techniques, has also been observed by others.[22]

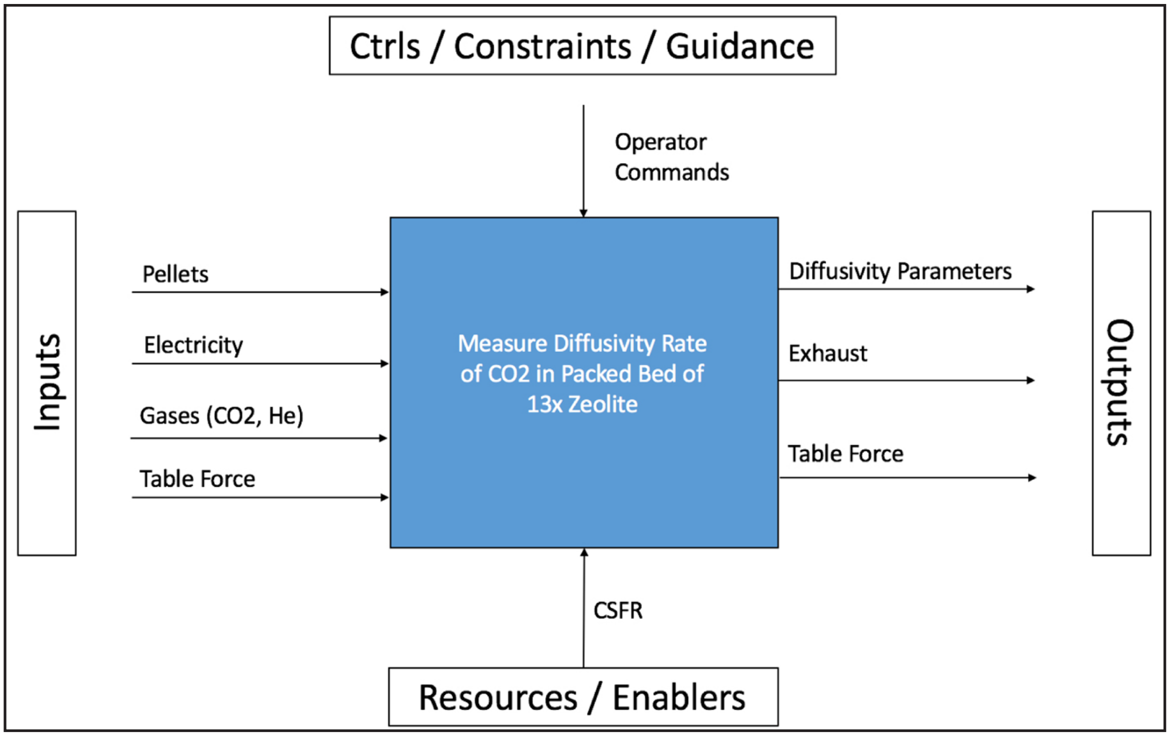
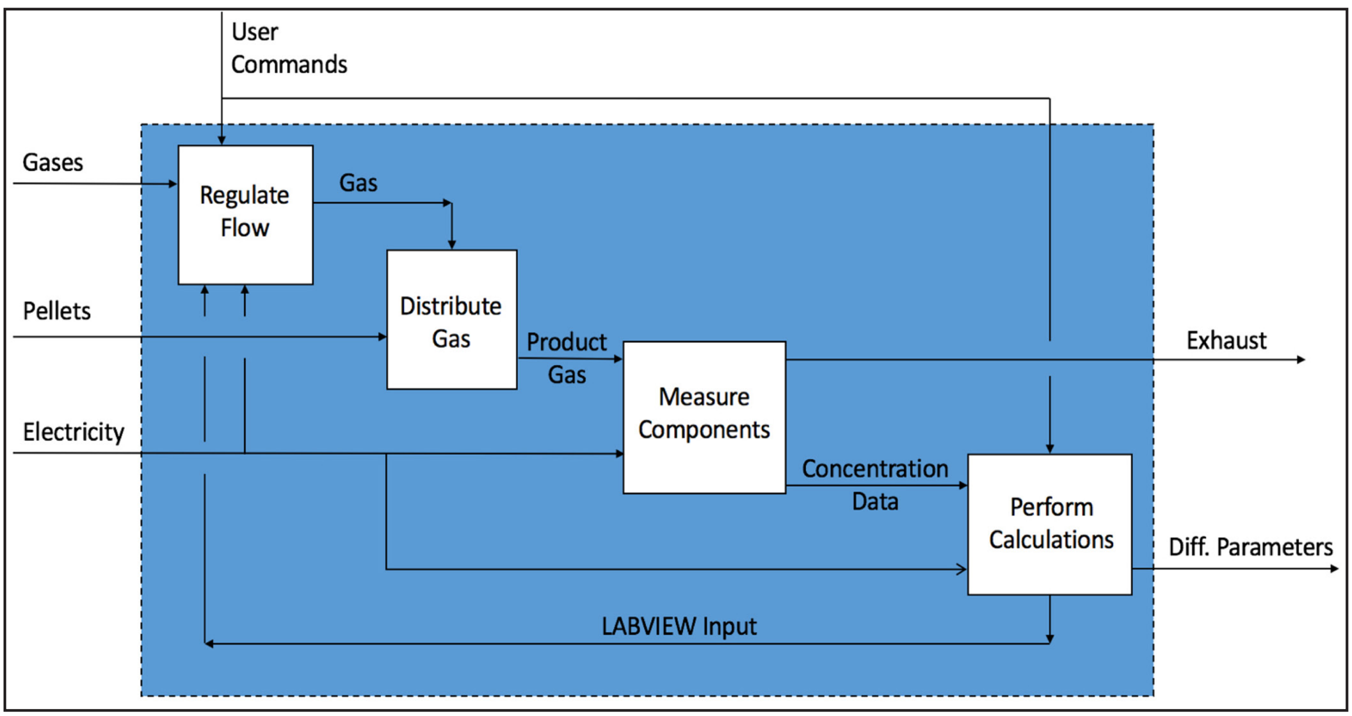


Figure 6, left. *Abstract context diagram developed by students.*

Figure 7, bottom. *Functional decomposition diagram based on inputs from Figure 6.*



The contrasting approach between the X-Hab students and the traditional chemical engineering students also arises from the differences in the expected work product from these efforts. Specifically, the students in the X-Hab project were expected to develop a tangible working apparatus that, as a result, required not only envisioning architecture, but also ordering the parts and assembling the device. The expectation of an assembled device also forced the X-Hab students to manage a budget and ensure that each part was correct because there was very little additional funding to allow for errors.

In contrast, traditional capstone design projects result in a written report as the final work product. The absence of a fixed budget and completed device results in traditional students working through the project only as an academic exercise.

With this recognition, it would be beneficial to constrain the traditional design projects to a hypothetical budget and penalize the students if the budget is exceeded. This approach, coupled with short lessons on systems engineering concepts, would allow the students to ensure they meet stakeholder expectations (the hypothetical budget), and avoid down selecting to a physical architecture too early by utilizing systems tools, such as a context diagrams.

Lastly, students who have worked on the X-Hab project state that the experience has had a meaningful impact on their future success. In two out of four years the class was taught, a student has decided to continue to work on the project as either a chemical engineering or systems engineering graduate student. Other students have listed the experience on their resume and many have reported that discussing systems engineering within the context of a funded project was helpful in securing a job. One student, who now works for a government contractor developing systems for rockets, authored a letter to the university detailing the impact of the course on his job search.

TEACHING THE COURSE WITHOUT EXTERNAL FUNDING

In the Fall of 2017 funding for this course was not secured; however, because only the project design occurs in the Fall and the construction of the designed apparatus not until Spring, the Fall portion of the course could still be offered without the final construction phase. In this case, the students were divided into three teams of seven (groups selected by the students) and told to design a column of any type that was capable of performing a separation for use in the chemical engineering undergraduate laboratory. Students were provided with a set of constraints that were very broad:

- *intrinsically safe design*
- *physically no larger than approximately 6' tall, 3' deep, and 8' long*
- *limited waste production*
- *minimized cost*

The students were expected to interpret these constraints as appropriate for the intended application in the undergraduate lab. The students were also expected to apply systems engineering tools to determine the ideal design and then complete chemical engineering calculations, including Aspen simulations, to show the effectiveness the design.

Each of the three groups proposed different design solutions: a distillation column, an absorption column, and an adsorption column. If the same type of column had been proposed by all three groups, then systems engineering methods would have been applied to down select to a preferred detailed design. The students submitted a final report to the department and the department was tasked with identifying if any of the designs were suitable for construction.

The outcome of this course was similar to the previous externally funded projects; however, because the proposed devices were tools used to illustrate chemical engineering fundamentals, the calculations performed by the students were better connected to their undergraduate coursework. In general, the students underestimated the importance of controls software and struggled to identify how to develop control systems for the columns.

LESSONS LEARNED

A list of lessons learned from teaching a funded project undergraduate course for four years follows.

Class size

When the class size exceeds 15 students the class should be divided into multiple design teams. With multiple design teams, each team can design unique hardware or the same piece of equipment and each student can make a meaningful contribution. With four to five students managing the project and assigning tasks to other students, it is not uncommon in a group larger than 10 that some students either choose to minimize their participation, or are not assigned meaningful tasks to compete. Broad student participation was achieved in the Fall of 2017 when the class was taught without funding and multiple design teams were used.

Limited work experience

Instruction of systems engineering concepts via a traditional textbook and lecture should be completed with the recognition that most undergraduate students have little, if any, work experience. Specifically, concepts are generically presented in systems engineering textbooks for broad application to many projects and situations. However, when the concepts are presented generically, and when the students do not have any work experience to pair with the general concepts, the information is confusing and redundant. For students with internship or co-op work experience this problem was less prevalent because they can recall work experiences where problems could have been prevented by using systems engineering methods. Weekly quizzes on the concepts presented in the systems engineering textbook, followed by discussion of the concepts as they apply to the X-Hab project, helped minimize this problem.

Software design is important and should begin early

In all cases, software design was critical to the operation of the device. In the first offering of this course, the integration of software was completed too late in the development of the project, leading to the development of many different LabVIEW control software iterations. Later projects integrated software development into the design continuously throughout the project development. The best outcomes were achieved when the software engineer on the project was a chemical engineering student with knowledge of LabVIEW.

Ordering all the parts at the end of Fall semester is critical to compete the construction in the Spring

The students had to make decisions quickly and accurately, to make sure that parts were not simply selected, but purchase orders completed by the end of the Fall semester.

Course could be offered to all engineering disciplines

Finally, it is reasonable that the course could be offered as an engineering elective open to all engineering seniors. With this approach, a larger class comprised of different engineering majors could be divided into several groups, each designing different complex systems using systems engineering techniques. Broadening the course would promote teams comprised of students with different technical backgrounds, which would more closely resemble real-life industrial projects that are developed by a team of experts.

CONCLUSIONS

The X-Hab Innovation Challenge has played a key role in the development of the University of South Alabama's undergraduate elective in systems engineering. The course provided the students an opportunity to apply systems engineering concepts to a funded project over a two-semester period of performance. This course was developed specifically in response to a NASA project, but in the absence of funding was used to develop equipment for the Unit Operations Undergraduate Lab. The feedback from this course has been favorable both from students and local practicing engineers. Many students report listing the experience on their resumes. With systems engineering concepts becoming more prevalent, this course was a valuable elective option to undergraduate students and provided the students a first step towards developing technical leadership skills.

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