Development of an Innovative Multidisciplinary Course in Systems Analysis

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Abstract

The Systems Analysis course is innovative in three aspects: 1) analysis applied to systems of multiple domains and multidisciplinary systems; 2) use of pedagogies of engagement; and 3) instruction in qualitative and quantitative analysis. The theories of System Dynamics, Dynamic Systems, and Optimization are woven together with concepts from engineering design, engineering science, and sustainability taught in other courses in the curriculum. A five stage analysis process is utilized to provide structure for the course content, as well as model the complete analysis thought process with feedback loops scaffolding the students in their application and synthesis of the course material. A variety of pedagogical approaches, including deep, collaborative, and problem-based learning, have been utilized to develop the course learning activities and materials. The aim is to teach skills, and not content. To ensure that skills are developed, in-class challenges are given for each of the analysis stages, deep learning assignments are given at major milestones in the course, and students complete a course project. Many assignments require justification of answers to break the student mentality of “what is the right answer” and lead them toward developing solutions that address system requirements and balance tradeoffs. The reflection that comes along with justification solidifies concepts and enables mastery of the systems analysis process.

Introduction

The engineering program at James Madison University provides an emphasis on engineering design, systems thinking, and sustainability. Our young engineering program has been designed to train the Engineer of 2020 [1,2]. Offering a single Bachelor of Science degree in engineering without discipline-specific majors or concentrations, the goal is to train and produce engineering versatilists, a term popularized by Friedman [3], who can work in cross-disciplinary environments. At the heart of our program is the six-course engineering design sequence that provides instruction on design theory (thinking, process, methods, tools, etc.), sustainability, ethics, team management, and technical communication (both oral and written), while incorporating elements of engineering science and analysis. Students apply design instruction in the context of two projects during the six-course sequence—a cornerstone project spanning the fall and spring semesters of the sophomore year, and a capstone project spanning the junior and senior academic years.

The curriculum of our non-discipline specific engineering program, shown graphically in Figure 1, combines a campus-wide, liberal arts general educational core with courses in math, science, engineering design, engineering science, business, systems analysis, and sustainability [4,5]. Individual skills taught developmentally through the curriculum, beginning with the freshman year, are blended with engineering design theory and utilized in projects in the design sequence. During the engineering design courses, students not only learn engineering design tools and methods but also learn about creativity, sustainability, business, ethics, values, engineering science, math, and manufacturing. It is during this engineering design sequence where students are provided with a hands-on environment to apply the theory learned in other courses [6]. Similarly, the engineering science courses provide an opportunity to apply the theory and problem solving processes learned in the engineering design courses.
All students within the program are required to take courses in engineering science (statics and dynamics, thermal fluids, mechanics and materials, circuits and instrumentation, and systems analysis), engineering design, engineering management, and sustainability. Systems Analysis is the culminating engineering science course in the curriculum, and as such, it builds off of all prior engineering science coursework and integrates engineering design course knowledge through both qualitative and quantitative analysis of complex systems.

The Systems Analysis course is innovative in three aspects: 1) analysis applied to systems of multiple domains (i.e., electrical, mechanical, fluid, social) and multidisciplinary systems at the undergraduate level; 2) use of pedagogies of engagement; and 3) instruction in qualitative and quantitative analysis. The instructional goal is to not be discipline specific, but rather convey the multidisciplinarity of “real” systems problems. The ability for future engineers to work in cross-disciplinary environments is an essential competency as is the ability to think about the whole system at different levels of fidelity and in different time scales. To teach these skills to our students, the theories of System Dynamics by J.W. Forrester, Dynamic Systems (also referred to as System Dynamics), and Optimization are woven together with concepts from engineering design, engineering science, and sustainability taught in other courses in the curriculum. Engineering students are generally very good at applying quantitative analysis skills gained from engineering science courses to single domain systems, but fail to understand how those skills fit within the bigger system analysis picture or apply to multidisciplinary systems, and where to begin if the system is not predefined. To develop students’ non-quantitative analysis skills, and to hone their quantitative analysis skills for complex systems, a five stage analysis process is introduced. The five stage process aims to not only provide structure for the course content, but also, to model the complete analysis thought process with feedback loops scaffolding the students in their application and synthesis of the course material.
It is well known that engineering involves integrating broad knowledge towards some purpose, generally to address a need or solve a problem. As we move into a global future, engineers can no longer isolate themselves and must be prepared to work across disciplinary, cultural, political, and economic boundaries. The ability for future engineers to work in cross-disciplinary environments is an essential competency [1-3]. Furthermore, with greater emphasis being placed on understanding social, economic and environmental impacts of engineered solutions, another essential competency is the cognitive flexibility or adaptive problem solving skills to think about the whole system at different levels of fidelity and in different time scales [7,8]. Meaning decision making will be more complex and, consequently, engineers will be expected to make and justify their decisions considering the broader technical and non-technical impacts. Researchers emphasize that adaptability can be displayed at any stage of skill development, from novices, to advanced learners, to experts [9], and is not a matter of the quantity or quality of knowledge acquired, but rather how that knowledge is used to support high-level reasoning processes and problem solving strategies [10]. Embedding opportunities for learners to build and adapt their knowledge and skills throughout their learning experiences not only results in adaptive problem solving, but prepares learners for future learning [11]. For curricula to be effective, learners need to engage in deliberate, explicit reasoning [9].

Engineering curricula often heavily emphasize scientific and mathematic calculations or quantitative analysis and lack instruction in qualitative analysis. While quantitative mastery is valuable, it is equally important for students to use results to assess problems within systems and make necessary adjustments as well as to understand the trade-offs associated with their decisions [12,13]. Furthermore, engineering students are generally very good at applying quantitative analysis skills gained from engineering science courses to single domain systems, but fail to understand how those skills fit within the bigger system analysis picture or apply to multidisciplinary systems, and where to begin if the system is not predefined. Thus, they need training in both qualitative and quantitative analysis methods. To teach these analysis skills to our students, the theories of System Dynamics by J.W. Forrester, Dynamic Systems (also referred to as System Dynamics), and Optimization are woven together with concepts from engineering design, engineering science, and sustainability taught in other courses in the curriculum. This blending facilitates qualitative and quantitative analysis to make informed decisions and to be able to justify their decisions about a variety of systems and at different scales.

The theories of System Dynamics, Dynamic Systems, and Optimization have traditionally been offered as stand alone courses where students gain significant depth in the topic, and tend to be very theoretical. Each, however, contributes a valuable approach to the analysis of engineered systems. What this structure lacks is a way to build connections among theories and recognize when one should be applied over the other, or when qualitative analysis is enough. By weaving them together in one course the connections can be clearly established and foster the development of cognitive flexibility. The trade-off is lack of depth in any of the theories, but the students understand the broader context of system analysis and the technical and non-technical impact of their engineering decisions.

System Dynamics is an approach to policy analysis and design, and applies to “literally any dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality” [14-16]. Strengths of System Dynamics theory is its approach to qualitative analysis including articulating the problem and defining and representing the complexities of the system, and implementing policy changes based on insights. Dynamic Systems theory grew out of mechanical and electrical engineering and is focused on the development of mathematical models using ideal or lumped elements and ordinary differential equations (ODEs) [17,18]. Further, dynamic systems is closely coupled with system modeling for control systems, and the quantitative approaches to evaluate the models are the same regardless of sub-discipline represented. Representation is also key to developing the mathematical models as well as interpreting the system behavior. Optimization is a mathematical
approach for solving quantitative problems that utilizes an objective function that is to be maximized or minimized within a set of constraints and variables [19,20]. Early applications were in production planning and economics, but the concepts are broadly applicable to technical and non-technical systems [20]. A hallmark of optimization theory is decision making based on trade-offs. All three theories involve qualitative and quantitative analysis and their strengths are emphasized in the innovative course.

The Systems Analysis course was selected as a teaching innovation for the 2013 Frontiers of Engineering Education (FOEE) Symposium hosted by the National Academy of Engineering in Irvine, CA. In this paper the Systems Analysis course and how it is implemented are explained. The remainder of the paper focuses on lessons learned, conclusions and future work.

Systems Analysis Course Overview

The Systems Analysis course is the culminating engineering science course in the curriculum, and as such, it builds off of all prior engineering science coursework and integrates engineering design course knowledge through both qualitative and quantitative analysis of complex systems. Specific course topics are outlined in Table 1. Upon successful completion of this course, students will be able to:

- Articulate and apply the basic concepts associated with systems analysis.
- Identify and define the inputs/outputs, parts of system, and interactions.
- Develop system representations at multiple levels of fidelity.
- Develop mathematical equations that govern the system.
- Evaluate and characterize system performance.
- Accurately and appropriately use modeling tools for analysis.
- Identify and evaluate trade-offs to make informed decisions.
- Synthesize and apply systems thinking, principles, and tools to complex systems.

The goal for students completing this course is to leave with the skills necessary to analyze multidisciplinary systems and make informed decisions while considering trade-offs. The instructional goal is to not be discipline specific, but rather convey the multidisciplinarity of “real” systems problems. Thus, the course is considered multidisciplinary based on the analysis techniques taught in the course, and not based on the students that take the course. Only engineering seniors take the course. Lastly, the course prepares students for the systems analysis portion of the Fundamentals of Engineering Exam.

<table>
<thead>
<tr>
<th>Topics Covered:</th>
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<tbody>
<tr>
<td>1. Systems thinking, principles, and tools</td>
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<td>2. Qualitative and quantitative approaches to analysis</td>
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<tr>
<td>3. System inputs/outputs, order, assumptions, hierarchy, interactions</td>
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<tr>
<td>4. Dynamic system representation with diagrams and feedback loops</td>
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<td>5. Mathematical modeling</td>
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<td>6. System response and performance</td>
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<td>7. Optimization</td>
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<td>8. Linear Programming</td>
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<tr>
<td>9. Trade-off evaluation</td>
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<td>10. PID control</td>
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The innovative course is a semester long experience that facilitates students’ ability to synthesize and apply systems analysis principles and tools to complex systems. The course is innovative as it blends the theories of System Dynamics, Dynamic Systems, and Optimization to provide instruction in both
qualitative and quantitative analysis, and the course is designed to promote active learning of the different theories by using pedagogies of engagement [21]. Analysis is applied to systems of multiple domains (i.e., electrical, mechanical, fluid, social) and multidisciplinary systems at the undergraduate level. The techniques used in the theories are applied across disciplinary boundaries, which is appropriate for a non-discipline specific engineering program. At the undergraduate level, instruction in modeling of multidisciplinary systems is typically found in a controls systems course in mechanical or electrical engineering and is used to define the plant with specific intentions of developing a controller and not analyzing the system itself. At the graduate level, courses on system modeling or multidisciplinary optimization are common, but do not blend theories. Students in the Systems Analysis course at James Madison University experience the big picture to the small picture and how to work at the different levels between. Students also develop a fundamental understanding of the purpose of analysis and the system to be analyzed as well as how to make informed decisions for existing and conceptual systems. Knowledge and skills to identify a system, decompose it into parts, define interactions, develop mathematical models of system behavior, evaluate and characterize the models (using computational tools when necessary), and apply control measures if necessary are developed.

To develop students’ non-quantitative analysis skills, and to hone their quantitative analysis skills for complex systems, a five stage analysis process is introduced as shown in Figure 2. The five stage process aims to not only provide structure for the course content, but also, to model the complete analysis thought process with feedback loops scaffolding the students in their application and synthesis of the course material. Furthermore, the five stage analysis process provides structure for the course content and organizes the multiple theories taught into a single framework.

![Figure 2: Five Stage Analysis Process & Course Roadmap](image-url)

The stages of the analysis process are defined as the following:

- **Define**: Defining the reason for analysis as well as the system to be analyzed.
- **Represent**: Creating an abstraction of the system being analyzed through schematics, block diagrams, or other visuals to assist with model generation.
- **Model**: Creating the mathematical model of the system being analyzed based on the representation created and assumptions defined.
- **Evaluate**: Obtaining a solution to the mathematical model of the system being analyzed to characterize behavior and determine trade-offs.
- **Decide**: Understanding the behavior and trade-offs of the system to make informed decisions.

**Implementation**

A variety of pedagogical approaches, including deep, collaborative, and problem-based learning have been utilized to develop the course learning activities and materials. The aim is to teach skills, and not content. To ensure that skills are developed, in-class challenge activities are given for each of the analysis stages, deep learning assignments are given at major milestones in the course, and students complete a course project. The instructor aims to provide learning opportunities that engage multiple learning styles as well as provide a developmental or scaffolding approach to move students up Bloom’s taxonomy. Some elements of the traditional lecture style are present, but students are also challenged to be interactive in class through asking questions and the use of pedagogies of engagement. Figure 3
provides a timeline of when the in-class challenge activities, deep learning assignments, and course project are offered with respect to the course content and five stage analysis process.

Problems or projects in industry do not have a right answer; rather, they have a set of requirements to meet. Therefore, many assignments go beyond just repetition to practice course concepts and require justification of answers, especially when confronted with competing design objectives, to break the student mentality of “what is the right answer” and lead them toward developing solutions that address system requirements and balance tradeoffs. The reflection that comes along with justification solidifies concepts and enables mastery of the systems analysis process.

![Figure 3: Timeline, Learning Activities and Materials Linked to Course Roadmap](image)

**In-class Problem-Based Learning (PBL) activities:** In-class, students work individually and cooperatively on challenge activities to practice course concepts and skills in a directed manner. The challenge activities, summarized in Table 2, are created based on the multi-dimensional Problem-Based Learning (PBL) model [22,23]. Following the PBL model, the in-class challenge activities vary in structuredness, complexity, and group-based collaboration. The motivation is that exposure to different types of problems will enable students to experience different modes of thinking, learning, and problem solving (leading to students that are versatile, adaptive problem solvers, and approach problems with cognitive flexibility). Some of the challenges offered throughout the semester are: problem articulation with objectives, variables, assumptions, and interconnections; system representation as schematics or
block diagrams; mathematical modeling of multidisciplinary systems based on representation; system response characterization; and decision making based on initial problem articulation to address tradeoffs, performance, design requirements, and broader impacts. The challenges allow for peer teaching and class discussions of what answers/decisions are justifiable, as well as an opportunity to clear up any misconceptions.

Table 2: Summary of In-class Activities

<table>
<thead>
<tr>
<th>Analysis Phase</th>
<th>Multidisciplinary Systems for In-class PBL Activities</th>
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<tbody>
<tr>
<td>Define</td>
<td>Coffee maker, Vehicle suspension, Land use planning, Wyndor Glass Co. manufacturing, Radiation therapy treatment design</td>
</tr>
<tr>
<td>Represent</td>
<td>Stereo speaker, Vehicle suspension, Student motivation to study in college</td>
</tr>
<tr>
<td>Model</td>
<td>Stereo speaker, Zombie attack, Vehicle suspension, Land use planning, Wyndor Glass Co. manufacturing, Radiation therapy treatment design</td>
</tr>
<tr>
<td>Evaluate</td>
<td>Stereo speaker, Zombie attack, Motor controlled valve, Vehicle suspension, City waste management planning, Wyndor Glass Co. manufacturing, Radiation therapy treatment design</td>
</tr>
<tr>
<td>Decide</td>
<td>Liquid level control, Vehicle suspension, City waste management planning, Radiation therapy treatment design</td>
</tr>
</tbody>
</table>

An example in-class activity is given Figure 4. This activity is structured and guides the students through the representation and model phases of the analysis process for an electromechanical system, a stereo speaker, across four slides. The activity begins with discussion and explanation of how a stereo speaker works. Often students are unfamiliar with how one works but recognize the components in the images. The instructor encourages students to look up information and become informed about the system. Following the discussion the challenge is stated. Students work in pairs to draw the representation of the system and then derive the equations based on the representation. During this time the instructor walks around and assists struggling students, encourages those far along to help their peers, and re-teaches concepts as needed. Once students are sufficiently along in answering the first question the answer is shown, so students can check their work and have a common basis for working on the second part of the activity. Once students are sufficiently along the answers are written on the board, so students can check their work and correlate the representation to the equations. The evaluation phase is covered a week later, and because the system has already been introduced students can build upon prior knowledge. This is the case for several of the systems used in class activities, which saves time but also encourages recall of information.
Deep learning assignments: Deep learning outside of class occurs through assignments designed for deep learning. Deep learning exercises employ the multidimensional design elements of an affective hook (conveys relevance), visualization, writing, justification, and reflection [24-28]. This ensures students have multiple ways of interacting with the material, which leads to deep learning. The pedagogical element of an affective hook conveys relevance, worth and links to an individual’s personal interests or experience [24]. Thus, the topic of the assignment must capture the interest of the students and be relevant to them. The pedagogical element of visualization means to explain by diagram or developing images of the knowledge (e.g., concept map, flow chart). Drawing engages psychomotor skills and helps to build a mental image [24]. The pedagogical elements of writing and justification involves developing text of the knowledge that includes explanation of reasoning [24]. Writing, similar to drawing, engages psychomotor skills through editing and reorganizing the work. The pedagogical element of reflection involves understanding their thought processes and what learning resulted. Students must think about and explain their thought processes, which helps them to achieve metacognition. For students to complete the individual deep learning assignments they must think critically and integrate new and existing knowledge, as the assignments require synthesis of multiple course concepts, identification of relevant information, balancing trade-offs, and justification of their recommendation and analysis process. The deep learning assignments are meant to give undirected opportunities to scaffold and prepare students to apply course concepts to their capstone project.
Each deep learning assignment provides a scenario to give context to the analysis as well as create the affective hook. Following the information are the instructions, which are organized according to the five stage analysis process. Additionally, the goal of the assignment, the deliverables, and how the assignment will be evaluated are given. An example of a deep learning assignment is given in the appendix.

**Course Project:** The course project requires students to apply course concepts, tools, and methods to one of two options: 1) their capstone project, or 2) a given alternative system. The engineering program at James Madison University is designed to accommodate a maximum of 85 students in the junior and senior years (total of 170 upperclassmen). Thus, all seniors take the Systems Analysis course in a single semester, which is the fall semester as shown in Figure 1, and can work together in teams for the course project. The course is placed at that point in the curriculum to explicitly facilitate the integration of engineering science and engineering design through the capstone project. The second year of the capstone experience at James Madison University builds upon previous design courses and also incorporates concepts and tools from mathematics courses and Systems Analysis. In Engineering Design V, students are in the embodiment phase of design, and Systems Analysis is a co-requisite for this design course. Students can apply the systems thinking concepts gained in Systems Analysis to their capstone projects to develop analytical prototypes that verify design parameters, trade-offs, and components. The content in Systems Analysis is aligned with the projected design phase of the capstone projects and integrates well with the design course.

As a culmination of course concepts, rather than a continuous process throughout the semester, the project is not started until after the second deep learning assignment. The course project, also grounded in problem-based learning, is linked to the student’s capstone projects and is open ended, complex, and unstructured. During the project, students individually perform unique sub-system analyses which are then combined with their teammates’ individually performed analyses to create a full system analysis. Students are challenged to consider inputs and outputs of each analysis as well as determine appropriate justification in terms of elements, attributes, parameters, relationships, sustainability, and tradeoffs.

The goal of the course project is for students to work in teams to apply systems thinking, principles, and tools to analyze complex systems. It is an opportunity to perform engineering analysis on an existing, complex system and justify choices made during analysis. Emulating engineering practice. Throughout the project, knowledge and experience gained in class and through assignments is applied. Also, the hope is that students will become more comfortable working on open-ended problems as well as synthesizing course concepts. The deliverable is a system-level analysis that includes all five phases of the analysis process (course roadmap) given as a poster on the final day of class. Teams are encouraged to create panels that can be printed on 8.5”x11” sheets of paper, which can then be pieced together to form a poster.

The in-class activities are not graded and serve as formative assessment, while all other evaluations of student performance, as summarized in Table 3, serve as summative assessment.

<table>
<thead>
<tr>
<th>Course Element</th>
<th>Percent of Grade</th>
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<tbody>
<tr>
<td>Homework, Quizzes</td>
<td>10%</td>
</tr>
<tr>
<td>Deep Learning Exercises</td>
<td>10%</td>
</tr>
<tr>
<td>Course Project</td>
<td>25%</td>
</tr>
<tr>
<td>Mid-term Exam</td>
<td>20%</td>
</tr>
<tr>
<td>Final Exam</td>
<td>35%</td>
</tr>
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</table>

*Table 3: Student Grade Breakdown*
Lessons Learned

The course is in its fourth year. In the first year, the course focused equally on qualitative and quantitative analysis, and students worked on a project unrelated to capstone in the final weeks of the course. In the second year, the five stage model of systems analysis was implemented, optimization theory added, and the course project was implemented incrementally throughout the semester. In the third offering, bench-top physical systems were integrated into the course to allow students to see theory in action, especially the PID control mathematical models, and gain a deeper understanding of how assumptions and interdependencies affect analysis. Also, a second option for the course project was offered to provide the student teams an opportunity to analyze a system other than their capstone project. In the forth year one of the dynamic systems deep learning assignments was replaced with an optimization themed deep learning assignment to balance the assessments with the course concepts.

Overall, the course has been very successful and embraced by the students. Students appreciate the opportunity to apply prior math and engineering course knowledge for analysis of complex technical and non-technical systems. The integration of software into the course is appreciated as many of the students want to learn how to develop mathematical models. Students are taught how to accurately and appropriately use software-based modeling tools (e.g., matlab, lingo) for analysis, and by the end of the course, students develop an appreciation for qualitative analysis and how it is vital to quantitative analysis and decision making. Furthermore, a deeper understanding of how the system operates is developed, which enables them to make sense of outputs, dependencies and opportunities for optimization and control.

What has worked for the course:

• Providing the course roadmap helped students mentally organize the multiple theories covered in class as well as provided a framework for organizing the course. In the initial course offering the process models were shown for each of the systems theories and it caused quite a bit of confusion. To unify and organize the qualitative and quantitative course concepts along the five stage analysis process was created.
• In-class Problem-Based Learning (PBL) activities that bring together multiple concepts provide a structured environment for learning and applying the tools associated with the phases of analysis. The active learning activities also scaffold the thought processes necessary for applying the course concepts to engineering problems. Students appreciate the chance to practice the concepts in teams before trying them on their own.
• Deep learning assignments engage students in an authentic application of course concepts and allow practice of unstructured systems analysis before attempting the course project. Past student evaluations expressed concern over homework being more like busy work and not challenging or application focused. Student evaluations included mixed reviews about the deep learning assignments. Some thought they took too long, or were too hard. Some loved them and felt that the assignments helped them to learn the course material better. Students overall appreciated being able to work in teams.
• Having an alternative system (Option #2) for the course project to give students choice if they felt their capstone project could not benefit from application of the course material. Past student evaluations expressed concern that not all capstone projects fit the course model and it was unfair. Student evaluations did not express concern about course project, rather the opposite was found in the comments.

What has not worked for the course:

• When co-instructors divide up the course based on expertise and teach only the concepts they are comfortable with. This leads to a disjointed message (and language) regarding course concepts
and policies, especially when instructors have different teaching philosophies. It is better to have a single instructor that is not an expert in all of the concepts than multiple instructors that are experts in the concepts they teach.

• Capstone teams that have a non-physical capstone project system have difficulty with the course project. Students are given the chance to choose the system theory or theories that best apply to their capstone project system, but seem to struggle when the project focuses on developing an analytical tool or the physical embodiment did not exhibit dynamic changes. This lead to providing teams another option for the course project.

• Allowing students to pick any interesting complex system to model. This freedom resulted in creation of mathematical models that had no other purpose than to show that it is possible. While is provides the motivation for application of the model and evaluate phases, it does not reinforce the value of the define, represent, and decide phases. Essentially they are just creating a mathematical model to create a mathematical model. It has no real purpose and does not tie together all course concepts.

• Using multiple software packages throughout the semester tends to overwhelm the students and they focus less on the problem solving and more on the tool. The time to learn a new piece of software took too much time away from using the software to implement analysis. This lead to the use of Matlab as the only software package used in the course.

Conclusions and Future Work

The curriculum of our non-discipline specific engineering program combines a campus-wide, liberal arts general educational core with courses in math, science, engineering design, engineering science, business, systems analysis, and sustainability. Thus, the curriculum is integrated to help tie together fundamental concepts with Systems Analysis being the culminating engineering science course. The course pushes students to become comfortable with open-ended problems to break the student mentality of “what is the right answer” and lead them towards developing solutions that address system requirements and balance tradeoffs. The five stage analysis process scaffolds students through the process of analysis. The deep learning assignments and course project assist with building cognitive flexibility. Overall, the course is successful at building students' qualitative and quantitative skills in making informed decisions about multidisciplinary systems while considering the broader technical and non-technical impacts. One recommended change is to greater emphasize that the analysis techniques from systems dynamics, dynamic systems, and optimization are multidisciplinary, not just the systems that are analyzed. Future work also includes the integration of codes and standards, which would only continue to bring more exposure to practical engineering skills.

References

Appendix
Deep Learning Assignment
Lunar Lander System (60 pts.)

Scenario:
Rocket transport vehicles, which usually land on terrestrial bodies, use a three-legged or four-legged landing system. Each leg consists of a spring and damper within a tube. Both the spring and damper are connected to the foot (foundation) of the device, which has a large enough area not to sink into the ground as the vehicle compresses the landing device. At the instant of landing, the vehicle (mass $M$) has an initial velocity $V_o$. The objective of the landing device is to cushion the blow of landing without bouncing. As the vehicle lands, the spring will compress, and, at the same time, the damper will absorb the energy. If the total mass is $M_t$ and each of the legs makes an angle $\theta$ with the vertical, model the elements of this system.

DEFINE
Problem Articulation for Lunar Lander
1. Reason of Analysis – Design the lunar lander to cushion the blow of landing without bouncing.
2. System Boundary – The four-legged system shown in the image below.

![Diagram of Lunar Lander System](image)

3. Key Variables –
   a. Input – None. There is no gravity in space.
   b. Output – Vertical linear displacement of vehicle body, $x$
   c. Parameters:
      i. Mass of vehicle = 646 kg
      ii. Mass of payload = 1354 kg
      iii. Angle $\theta$ = 0.5 rad
      iv. $V_o$ = 10 m/s
      v. Spring stiffness, $k$ = 5730 N/m
      vi. Damping coefficient, $c$ = 811.5 N*s/m
      vii. Initial conditions:
         1. $x(0) = 0$
         2. $dx/dt(0) = V_o$
4. Interconnections – There are no sub-systems to call out of this system. The vehicle mass is comprised of the landing device, the body and the payload. The spring and damper work in parallel to absorb energy when coming in contact with the ground and release energy to bring the system back to an equilibrium state.
5. Assumptions:
a. Equal distribution of weight across all four legs.
b. Equal vertical, translational displacement across all four legs during compression.
c. No gravity in space.
d. Assume mass of the payload and initial velocity cannot change.
e. The displacement of each leg that makes an angle \( \theta \) with the axis of translation during decent (compression), affects the response of the spring and damper elements. The angle \( \theta \) of each leg must be accounted for, however, because \( \theta \) changes only slightly during decent the resting angle can be used. Thus, the effective spring constant and damping coefficient at an angle can be accounted for using the following two equations:
   i. \( k_{\text{angle}} = k \cos^2 \theta \)
   ii. \( c_{\text{angle}} = c \cos^2 \theta \)

Instructions:
Perform the REPRESENT, MODEL, EVALUATE, and DECIDE phases of analysis for the lunar lander system design following the given information in the DEFINE phase. **Work in a team of two** to develop the following:

**REPRESENT**
1. *Develop a technical system schematic representation.*
   a. Represent the system using ideal elements in schematic form.
   b. Label all items.
   c. Define the positive direction of motion.
   d. Justify your schematic representation. Meaning explain how your representation links to what is specified in the Problem Articulation.

**MODEL**
1. *Develop the system equation(s) from the technical system schematic representation.*
   a. The equation(s) should be symbolic and in a standard form.
   b. Define all equations variables.

**EVALUATE**
1. *Obtain the response of the mathematical model of the system being analyzed to understand behavior.*
   a. Using software, create a response plot of the output using the given parameters, and label it ‘Original Lunar Lander System Response when Landing’.
   b. How does the dynamic response obtained relate to the reason for analysis?
   c. Characterize the system order, performance, and stability. Justify your answers through equations, graphs and/or matlab code.
   d. How long is the transient period? How does it affect the system?

**DECIDE**
1. *Using the data collected from model evaluation, make informed decisions and trade-offs to achieve the analysis objective.*
   a. Explain how the response can be improved to address the reason for analysis?
   b. What are potential trade-offs to the system design?
   c. Explain the decisions made to improve the system response and address the reason for analysis. Are the changes realistic? Discuss iterations made. Justify your answers.
d. Provide the final set of new system parameter values as a result of the decisions made. **Show all work.**
e. Using software, create a response plot of the improved system response, using the new system parameter values and label it 'Improved Lunar Lander System Response when Landing'.

**Reflection**
- Provide a one paragraph reflection.
- Discuss the thought process taken when analyzing the lunar lander system. Elaborate on steps taken and how decisions were made.

**Optimization**
- Explain how optimization could be applied to the lunar lander system. What variable(s) would you choose and why? What would be maximized/minimized?

Submit: A typed written hardcopy of your work **submitted electronically through canvas.** *Cite any and all references in APA format.* Diagrams can be hand drawn if neat, but must be submitted electronically. It is suggested that you use a software program to prepare the diagrams.

**Assignment Goal:** Provide students with the opportunity to perform engineering analysis on an existing, multidisciplinary system and justify choices made during analysis. Also, the hope is that the student will become more comfortable working on open-ended problems.

**Evaluation:**

<table>
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<tr>
<th>Assignment Components</th>
<th>Points Possible</th>
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<tbody>
<tr>
<td>REPRESENT</td>
<td>5</td>
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<td>MODEL</td>
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<td>EVALUATE</td>
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<tr>
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<td>Professionalism</td>
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**Extra Credit Opportunity (up to 10 pts.):** Set up, and solve the equations for the variable(s) to optimize as stated in the optimization section above.