121st ASEE Annual Conference & Exposition
Indianapolis, IN
June 15-18, 2014
Paper ID #9443

Introducing the Fundamentals of Systems Engineering to Freshman through Various Interactive Group Activities

Ms. Madeleine C Brannon, George Washington University

Madeleine Brannon is currently pursuing a M.S. in Systems Engineering. She received her B.S. at the George Washington University in Systems Engineering with a minor in mathematics in 2013. She is a Graduate Assistant to Professor Thomas Mazzuchi and works primarily as a Teaching Assistant within the Engineering Management and Systems Engineering department.

Prof. Zoe Szajnfarber
Dr. Thomas Andrew Mazzuchi, George Washington University

Dr. Thomas A. Mazzuchi received a B.A. (1978) in Mathematics from Gettysburg College, Gettysburg, PA, a M.S. (1979) and a D.Sc. (1982), both in Operations Research from the George Washington University, Washington DC. Currently, he is a Professor of Engineering Management and Systems Engineering in the School of Engineering and Applied Science at the George Washington University, Washington, D.C. At George Washington University, he has also served as the Chair of the Department of Engineering Management and Systems Engineering, Chair of the Operations Research Department and as Interim Dean of the School of Engineering and Applied Science. Dr. Mazzuchi has been engaged in consulting and research in the area of reliability and risk analysis for over twenty five years. He served for two and a half years as a research mathematician at the international operations and process research laboratory of the Royal Dutch Shell Company. While at Shell, Dr. Mazzuchi was involved with reliability and risk analysis of large processing systems, maintenance optimization of off-shore platforms, and quality control procedures at large scale chemical plants. During his academic career, he has held research contracts in development of testing procedures for both the U.S. Air Force and the U.S. Army, in spares provisioning modeling with the U. S. Postal Service, in mission assurance with NASA, and in maritime safety and risk assessment with the Port Authority of New Orleans, the Washington Office of Marine Safety, Washington State Department of Transportation, and the San Francisco Bay Area Transit Authority. Dr. Mazzuchi's current research interests include systems engineering processes, risk analysis, reliability growth assessment, software reliability modeling, design and inference in life testing, reliability estimation as a function of operating environment, maintenance inspection policies, and incorporation of expert judgment into reliability and risk analysis.

Introducing the Fundamentals of Systems Engineering to Freshman through Various Interactive Group Activities

Abstract

The concepts and tools taught in an introductory course to Systems Engineering involve a mindset which is not familiar to freshman undergraduate students and is slightly different from that needed for more traditional engineering disciplines. Teaching Systems Engineering at a freshman level is challenging because students do not have work experiences to draw from to solidify the tools they are learning. In order to overcome this barrier, immersive group activities were introduced to provide a simulated context in which students can apply and learn about the benefits of Systems Engineering. Thus, the Introduction to Systems Engineering course is structured around three group projects, which collectively provide an overview of the fundamental lessons of the field. The projects are an egg drop challenge which teaches the value of upfront Systems Engineering and rapid prototyping, a LEGO Mindstorms™ competition which teaches the importance of problem decomposition, testing and validation, in addition to design under operational uncertainty, and a Lean Simulation game which teaches user needs, the importance of balanced work and enterprise value.

While it has been well established in the general pedagogical literature that group projects and active learning are effective teaching tools, they are not widely used in Systems Engineering for a variety of reasons. Creating realistic and accessible Systems Engineering problems is difficult in a classroom setting and coordinating effective group projects can be complex and costly. In this paper, we document our attempt to overcome these challenges and explore how they impact the student's learning experience. First, we compare the content of our Introduction to Systems Engineering to other similar undergraduate introductory Systems Engineering classes at peer institutions to identify core differences in our approach. Second, we measure the learning progress through class observations and feedback from the students. The class observations include our perceptions of how students' questions evolve over the semester and also the extent of their engagement. The feedback portion provides the results and analysis of a survey where students rate the projects in the course, exploring which projects successfully tied our learning objectives to their perceived knowledge of Systems Engineering.

I. Introduction

Systems Engineering is a relative newcomer to the engineering disciplines and requires a slightly different set of skill as noted in [3]:

> *"The uniqueness of systems engineering among all other engineering disciplines lies in its adherence to the gestalt-holistic philosophy. This implies having a comprehensive view of the system, basic domain knowledge of it, and understanding and incorporating the intra- and interconnectedness and interdependencies within and outside the system."*

As such, there has been much discussion (see for example, [14], [1], [7], [9], [3] and [16]), about what a Systems Engineering curriculum should be. Particularly important is the question of how to introduce young or inexperienced students to Systems Engineering concepts (see for example [16], [8], [15], and [2]). The consensus appears to be to introduce students to these concepts through hands-on experience, however, introducing students to these concepts and providing hands on experience in a first course is a tall order. In this paper, we present an overview of an effort to do just that via the revamping of our Introduction to Systems Engineering course for first semester freshman at George Washington University. Herein is described the planning and implementation of the course, the student feedback, and the lessons learned.

II. Curriculum Design

In planning for the course, a review of what peer universities were attempting was conducted. A list published by INCOSE in July 2013 of the Systems Engineering programs was used to derive programs for undergraduate students. Several universities were contacted from the INCOSE list, Table 1 represents the information obtained from these universities on methodologies. In addition to the responses below, 6 universities reported that they did not have an introduction to Systems Engineering course. The list is by no means comprehensive but gives a good overview of current approaches. A mixture of methodologies from standard lecture, to the use of case studies, to the use of projects and mixtures thereof can be found. A more comprehensive table of course objectives is presented in the appendix.

Table 1. Review of Introductory System Engineering Courses

University	Methodology
Auburn University	Quizzes, Lab Reports, Design Project
George Mason University	Arduino Project, Exams
Oakland University	Homework, Exams, Lab
University of Alabama, Huntsville	"Lecture and class discussion"
University of Arizona	Predominately Exams and a Design Project
University of Arkansas at Little Rock	Quizzes, Homework, and a Design Challenge
University of Southern California, Los Angeles	"weekly homework and a Research Paper"
University of Virginia, Charlottesville	Case Studies
Washington University in St. Louis	Homework, Exams, Research Project
San Jose State University, San Jose	Homework, Exams, Final Group Project
University of Minnesota-Minneapolis	"problem sets, a midterm exam, a final exam, and a final project"
University of San Diego- San Diego	Exams, Homework, Hands-on Project
Youngstown State University	Quizzes, Project, Exam

The goal was to make the course simple to implement and both easy and effective for the students to grasp the Systems Engineering concepts in a short (8 week) period of time. We relied on 3 proven projects to demonstrate the initial concepts and values of Systems Engineering: a modification of the well-known egg drop contest (see for example [5]), the Lean Enterprise Value Simulation LEGO Aircraft Manufacturing Simulation (see for example [12]) and the LEGO Mindstorms Maze Navigation Challenge (see for example [4]). These three projects could easily fit into a half semester course and were simple enough to explain to the students, while at the same time providing valuable reinforcement of Systems Engineering concepts, conveyed during the lectures.

The following mapping presented in Figure 1 illustrates the Systems Engineering concepts conveyed by each project. While this is by no means a comprehensive view of Systems Engineering, the team felt that these concepts both conveyed some of the core Systems Engineering concepts and were conveyable to inexperienced students in the short 8 week period in which the class had to function.

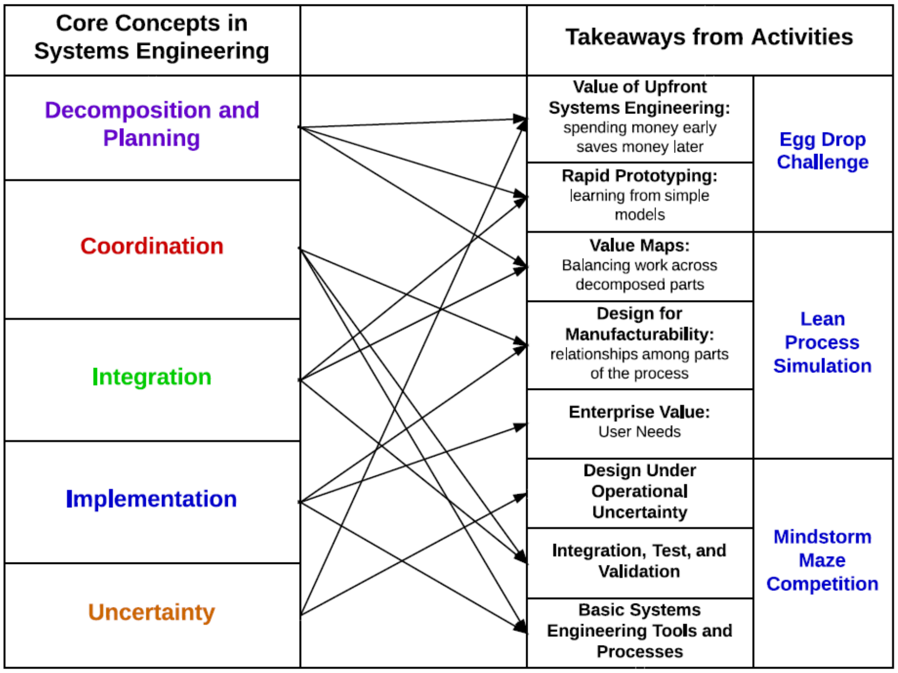

Figure 1. Mapping of Systems Engineering Concepts to Hands-On Projects

III. Class Setup

The 8 week long course, 1 credit course consisted of 18 freshman undergraduate students that met once a week for 2 hours and 50 minutes. The course is mandatory for Systems Engineering majors as well as any student with a minor or concentration in the field. The course is meant to be taken in conjunction with the School of Engineering and Applied Science 1001 course which is a class that all engineering students at the George Washington University are required to complete. There was no assigned textbook, however, students were asked to review the NASA

Systems Engineering Handbook [13] for the later part of the course to help them with their design documentation.

The teaching team consisted of an Assistant Professor, the Department Chair, and a Graduate Assistant who is a recent graduate of the Systems Engineering undergraduate program. The team encompassed useful perspectives and guidance for the students as an introduction to the department.

The main course learning objectives as outlined to the students in the syllabus were the following:

- Describe and explain the role of systems analysis in an engineering organization.
- Evaluate design tradeoffs associated with satisfying operational requirements in an uncertain environment.
- Decompose tasks among team members to efficiently balance work across available resources.
- Gain hands on experience designing and implementing a simple engineering system.

The course was structured to emphasize discovery-based learning and as such, lectures were not a predominant portion of the class and mainly provided a set up for the projects and concepts discussed in the class. That is, the lecture portion of the course was meant to familiarize the students with the concepts of Systems Engineering needed to properly complete their activities.

Three activities formed the bulk of the class work; the activities are listed in Table 2. The students' grade in the class was based on their class participation (25%), an egg drop challenge developed by MIT (10%), a Lean Enterprise Value Simulation developed by MIT Lean Advancement Initiative [12] (20%), and a LEGO Mindstorms Maze Navigation Challenge (45%). The grades were assigned for each activity based partially on individual student performance on exercises or quizzes and partially on student teams' performance in the activity relative to the mean performance of the class.

Table 2. Activity Schedule

Week	Activity
1-8	Lego® Mindstorms™ Maze Navigation Challenge
2	Egg Drop Challenge
2-5	Airplane Manufacturing Simulation

A. Week 1

In the first week of the course, the teaching team introduced themselves and the department. The first part of this lecture involved a curriculum overview intending to provide the students with a macro view of how all the project components were designed to fit together. The next part of the lecture gave the students a chance to meet the professors in the department. Most of the full time professors in the department came to the class and introduced themselves and their areas of research. Following the professor introduction, students were asked to introduce themselves to each other, and explain why they chose Systems Engineering and where they think they will be in 5 years. Afterwards, students were given an opportunity to mingle with the professors and familiarize themselves with the instructors and possibly express interest in certain areas of their research.

To give the students an immersive experience with design under operational uncertainty and experience with testing and validating of a simple system, students were introduced to the LEGO Mindstorms Maze Navigation Challenge. The students were split into six teams of three students and each team was given a LEGO Mindstorms™ Education NXT base kit. The base kit included three motors, an ultrasonic sensor, two light sensors, a sound sensor, two touch sensors, and LEGO building pieces. The teams were asked to come up with a team name and fill out an inventory list for their disassembled kits. By giving an inventory list, we wanted the students to immediately familiarize themselves with the different parts and sensors in the kit while giving them a sense of responsibility for the kit for the next seven weeks before the challenge.

The class was instructed that teams would be required to design an autonomous vehicle or robot from the kits provided which would be capable of navigating a semi-structured maze. The following conditions would be imposed:

- The only human interaction with the vehicle during the competition will be to press: "go."
- No outside materials are permissible.
- Navigation aids such as line or wall will be available at all points of the maze but not simultaneously.
- The robot should be able to stop on its own at the end of the maze.
- The specific structure of the maze will not be disclosed in advance.

Students were shown a video of the teaching team's LEGO Mindstorms completing a maze (see for example Figure 2) which encompassed both line and wall following. Suggested tutorials were outlined in the syllabus and each week's tutorials (see Table 3) were meant to build towards the student's success and understanding of the maze challenge at the end of the course. There were two demonstrations solicited during the course, a line and wall following demonstration to make sure that the students were on track to completing the final challenge.

B. Week 2

In the second week of the course, the idea of lean concepts in Systems Engineering was introduced. Students were provided examples of where lean concepts have helped enterprises and the general idea of making a process lean. The lecture was in anticipation of the start of the lean simulation the next week.

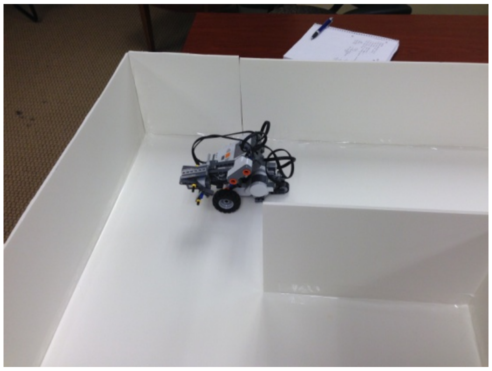

Figure 2. The LEGO Mindstorms Maze Navigation Challenge.

Table 3. LEGO Mindstorms Suggested Tutorials

Week	**Suggested Supplementary Tutorials in Preparation for Class**
2	Detect Dark Line Move Forward Reverse Curve Turn Drive in Square
3	Line Following Detect Touch Detect Distance React to Distance
4	Reset Rotation Sensor Bump Counter

After the lecture, students were introduced to the egg drop challenge to reinforce the values of upfront Systems Engineering and rapid prototyping. Teams of 3 to 4 students were randomly assigned for this activity.

To begin, students were briefed with the rules of the challenge. The objective of the challenge was to design, manufacture, and deliver three shipping cartons within a 60 minute deadline, each capable of protecting one uncooked egg from a drop of a height of 8 feet to a hard surface. The students were constrained to using the materials provided, each with a different fictitious price per unit:

- manila folder (min. order = 1 folder or 216 sq. in.) @$10/sq. in.
- stuffing (paper towels) @$100/sheet
- tape @$75/inch $
- staples (min. order quantity = 10) @$50
- paper clips @$10 each
- rubber bands @$100 each

Teams were told that they would receive a fictitious $500 reward for each successful shipping carton delivered (that is, one which protected the egg from the fall) at the 60 minute mark, and a $50 bonus for each successful carton delivered within 55 minutes. The goal was to achieve the greatest profit for the exercise. The prices were calibrated to enforce a tradeoff between upfront investment in testing and profit on delivery.

Teams were instructed to take a few minutes to assign roles to each of their team members. These roles were: design engineering (who takes the lead on the design phase of the project), purchase and finance (who retrieves and records the materials required for the designs), manufacturing (who takes the lead in the production phase), and quality control (who ensures the quality of the delivered product). The purchase and finance member was provided a cost sheet to record their purchases and turn in to the teaching team at the end of the challenge. The teaching team acted as the suppliers and only corresponded with the purchase and finance representative of each team. After the assignments were made the contest began (see Figure 3).

Figure 3. The Egg Drop Contest.

After the one hour of design and build time, the teaching team then dropped the eggs and inspected each shipping carton for success or failure of the eggs transport. The grades for the challenge were assigned based on the relative financial success of the team against the class average. The students were also asked to complete a one page summary of the lessons they learned during the challenge which was not graded but reviewed. The lessons learned which best exemplified the Teaching Team's objectives with the activity were used in a short debriefing at the beginning of the next class.

C. Weeks 3

During weeks 3 to 5, the students participated in a Lean Enterprise Value Simulation and started preparing for their LEGO Mindstorms™ Navigation Challenge.

In week 3, to begin the Lean Enterprise Value Simulation, the students were split into three teams or enterprises, and each was assigned a predetermined role. The roles included subsystem manufacturing, systems integration, supplier, and quality assurance representative. The enterprises' main objective was to deliver the most LEGO airplanes to the customer and make the greatest profit. As with the egg drop challenge, there were specified materials and ordering costs, time restrictions for delivery, and rewards for delivering fully and correctly assembled planes, however, the complexity of this exercise was far beyond the egg drop challenge (see for example Figure 4).

Figure 4. Lean Enterprise Value Simulation

Each member of the teaching team oversaw an enterprise team and acted as the customer. The teaching team was instructed beforehand on how to answer their team's questions. This was crucial to the success of the simulation. If the teaching team relayed incorrect information or misled their team in anyway the relative success of the student teams could be thrown off, however, the teaching team also had to be careful not to lead the student teams so that they could experience lessons learned from their mistakes.

Week 3 was used to familiarize each team with the simulation and the rules of their own roles in the manufacturing process. The students assembled LEGO airplanes in a representative multi-stage manufacturing process. Each team member followed his or her own "design-to" specifications, which collectively led to the delivery of a completed airplane that met the requirements of the customer. The customer or teaching team member then inspected the plane for quality. The goal was set to deliver 12 LEGO airplanes within a deadline of 12 minutes. After several rounds of the simulation were conducted to ensure the students understood the simulation and their respective roles, a final round was run and at the end, the profit for the round was calculated for each team. The simulation intentionally made students feel frustrated with the inefficiencies of their production process and inspired them to seek process improvements.

After the simulation portion of the class, week 3 concluded with a demonstration from each group that they were able to program a line following capability for the LEGO Mindstorms Maze Navigation Challenge. The line following maze was made from black masking tape placed onto a white poster board. The line curved slightly to test the robustness of their programs. The students were given feedback and graded based on whether their vehicle could line follow and how robust their program was.

D. Week 4

The class began again with part 2 of the Lean Simulation exercise. Having developed a baseline understanding of the airplane simulation process in week 3, week 4 focused on identifying areas for process improvement. Following a brief lecture on basic process re-engineering techniques, students were asked to create a value stream map of the current process, and calculate key metrics like takt times for the system. They were challenged to question if all of the steps followed by their enterprise were “value added,” directly contributing to the creation of the airplane. The students were given a fixed enterprise improvement budget and information about the costs for changes to their enterprise. They then determined how to improve the system and carried out the changes. Students noted improved performance but still fell short of the specified goal. In addition, some teams could see result of their improper design decisions.

After the simulation portion of the class, week 4 concluded by evaluating the Mindstorms challenge teams on whether their vehicles were able to demonstrate a wall following capability. The teaching team had a small and simple maze made of poster board which the robot needed to traverse. The maze included two left turns and one right turn to show the students programmed their robot for both scenarios. The teams were given grades based on completeness and how much improvement was suggested before the final competition.

E. Week 5

The class began again with part 3 of the Lean Simulation exercise. Where the re-design activity in week 4 focused on the process flow, week 5 explored how the design of the technical system can influence production effectiveness. A lecture on the concept of design for manufacturability was provided, discussing the value of common parts and the importance of balancing work across the value chain. Students were then asked to implement these ideas in the context of the simulation, changing the system decomposition into more balanced subassemblies, reducing the number of different parts (e.g., replacing two 2x4 white LEGO blocks with one 2x8 white block). After their redesign, a final round of the simulation was run and at the end, the profit for the round was calculated for each team. Teams were graded on the financial performance of the team with respect to the class average and on the number of airplanes produced in the final round.

Following the simulation, students were given a quiz on the lean concepts which they learned. The quiz gave the students an example of a manufacturing process and asked the students to create a value stream map of the process, calculate takt time, and identify how to Balance and 6S the process.

Week 5 concluded with a lecture on designing a test plan which would help the students with the test day for the navigation challenge. The lecture emphasized the importance of testing and creating a design which is flexible enough to account for reasonable variability. The students were assumed to have no statistical training and therefore, the lecture reflected their level of comprehension. Students were encouraged to think of the program they had created so far for their maze competition and what problems they could face if the maze was designed in a certain way which they had not yet anticipated.

F. Week 6

On week 6, students were given a brief overview of Systems Engineering since the class was now better acquainted with the concepts of the field. It was emphasized that Systems Engineering is the middle ground of management and engineering and provides tools to solve a range of problems. The lecture included design under uncertainty and a brief introduction to requirements and functional decomposition.

Also on week 6 students were given an opportunity to work with the teaching assistant to prepare for the LEGO Mindstorms™ Navigation Challenge. The students were asked to complete a test plan by the end of the class. The test plan would have requirements for the vehicle's program to successfully finish the challenge. They were also asked to specify any special conditions they would anticipate in the final challenge for the next week's test and calibration class. These conditions included mixture in lighting, curved turns while wall following, and different thickness of lines while line following.

G. Week 7

Week 7 was test and calibration day. Students were given the full 2.5 hours to fill in their validation matrix; each requirement was validated through test, analysis, demonstration or inspection. If a requirement was not met, a discrepancy report was produced outlining the cause of the issue and how it would be fixed. The discrepancy report was handed in as part of the final design documentation. In addition to testing to requirements, students were encouraged to think ahead about how they would calibrate their various sensors on the day of competition (discussed below). The teaching team was available during this time to answer questions they may have while formulating their algorithms for the final challenge.

H. Week 8

On the day of the competition, a fully disassembled kit was provided. Teams were given 30 minutes to assemble and calibrate their systems. After the allocated time, vehicles were moved to a holding area until its turn to compete. Each vehicle attempted to traverse three different mazes. The first maze was a line following only maze, the second a wall following maze, and the third a combined wall to line maze. The students were only allowed to use one program to complete each of the mazes, the idea being to demonstrate a design that was robust to a specific kind of operational uncertainty. At the conclusion, students were instructed to prepare their final reports to include system design documents, an operational plan, a test plan, and a summary of lessons learned. Student grades for this exercise were based on their performance on the inventory exercise in week 1, the demonstrations in weeks 3 and 4, their performance on the maze challenge, team peer evaluations, and their final report.

Week 8 concluded with an overview of the activities the students had participated in during the course and how they mapped to the course learning objectives. The overview emphasized the concepts of Systems Engineering that were demonstrated in the course and the future courses that would reemphasize what was learned in this introductory course.

IV. Class Observations

A. Egg Drop Challenge

The students generally enjoyed the Egg Drop Challenge. One of the students talked about how great it was to be immersed in a situation which challenged them to think in a different way. In general, the teams were focused on their designs for a 20 minute period during the start of the competition. Many of the teams drew a design even though we did not require them to and talked to each other about the physics that backed their ideas. One team split the responsibility to design and deploy their shipping containers and later found that inefficient. Only one team rushed to order to attain the bonus reward for delivering early and benefited from the extra points.

The class was very excited to watch the teaching team drop their containers and huddled around in anticipation. The class as a whole cheered and groaned when a design was determined to succeed or fail. The experience was an excellent way to integrate the students into the team aspect of our group activities. Students were forced to interact and share ideas. Overall, the challenge's positioning at the beginning of the class was beneficial to the class' familiarity with each other. The students also understood the importance of prototyping early and often, which was reflected in their one page summaries of the challenge.

B. Lean Simulation

The first day of the simulation was tough for the students. The class was frustrated because the simulation's rules were left intentionally vague and open for interpretation. The students were learning that they should not expect to be directed to the answers and would instead need to use critical thinking to come to their own conclusions. The teaching team was there to curb any frustrations and refer the students to the rules when they were confused and frustrated. The teaching team was also provided with general outcomes of the simulation in terms of possible upgrades and purchases the students could make which helped ensure the teams were on the right track and ultimately experienced the learning objectives. As the simulation continued, the students better communicated with each other during rounds of building and were excited to learn of upgrade possibilities. The teams were very strategic in trying to figure out how to maximize their performance under the given constraints. The students were particularly excited by the "design for manufacturability" part because in-product changes were more tangible than process changes. As the simulation progressed, during the building rounds, the teams were quieter because they no longer verified with other teammates their own tasks or corrected others. The teams learned how to interact more seamlessly with each other.

C. LEGO Mindstorms™ Navigation Challenge

The navigation challenge tested the student's abilities to both work as a team and engage in discovery-based learning. Since this was the only project completed predominantly outside of the allotted class time, some teams struggled to find meeting times and consequently team work was not necessarily evenly distributed. This caused some students to become frustrated in general with the challenge because they felt that they were doing an uneven amount of work. Our peer evaluation portion of their grade was set in place to counteract this attitude.

Throughout the challenge, students would come to the Teaching Assistant's office hours and ask for help on a piece of the program which seemed to not be working. Most of the teams with questions about their program were told to write out the logic of the program and think through the possibilities of the problems with the program on their own. At first, the student's expected to be helped and told what was going wrong with their approach but eventually learned to ask better questions and only refer to the Teaching Team when they had already thought about the possible problems attributing to the failure of their program.

During the competition, students were excited. The class seemed skeptical of their success in the challenge but enthusiastic to see the outcome of all of their hard work. When the competition started, the students were handed a disassembled kit and given 30 minutes to assemble and test their robots. Some of the teams came with booklets of steps for assembling with team member assignments in each step and pictures of the subassemblies. After the assembly period, each team attempted to traverse the mazes. The entire class watched and cheered for the robots as they attempted to complete the maze. Unfortunately, no team was able to successfully navigate a maze. The students were then given a ten minute break where they were able to test their robots further, identify the possible problems that led to their failure, and then chose any of the three mazes for a bonus round. Again the teams did not succeed in the bonus round, but they were much closer than in the previous part of their competition. Many of the teams attributed their failure to assembling the wheels incorrectly, uploading the wrong program to their NXT brick or microcontroller, and increased battery power. The student's better understood the value of testing and creating a robust program after the competition.

V. Class Feedback

On the sixth week of the class, the students were asked to participate in a voluntary survey which would provide feedback on the course's success in teaching the outlined learning objectives. Out of the 18 students, 14 decided to take part in the evaluation. The questions included:

- Which activity they enjoyed the most
- Which activity added the most to their perceived understanding of Systems Engineering
- How well they feel they understand the discipline of Systems Engineering after taking the course
- Which of the class modules mapped to the learning objectives

In response to the question of perceived understanding of Systems Engineering concepts, the class responded with an average of 3.93 out of 5, showing that student's felt they better understood the discipline of Systems Engineering. The rating is good feedback because the goal was for students to have a base knowledge of Systems Engineering but also be aware that they will have an even better understanding of the concepts as their education within the department continues.

In Figure 5, the activity ratings are provided and it is obvious that overwhelmingly students responded that the Lean Simulation contributed the most to their perceived knowledge of Systems Engineering. The Egg Drop was the most enjoyable activity, with 9 responses. The LEGO Mindstorms Challenge was unpopular, with only 1 response that it was the student's favorite activity and 0 responses providing that it added the most to their handle on the concept of Systems Engineering. The survey was given out during a time when the students had completed the Lean Simulation and Egg Drop Challenge, but were still working on the LEGO Mindstorms Challenge. The uncertainty of their competition and frustration over the amount of work which team's had left to do may have contributed to the activities' lack of positive feedback.

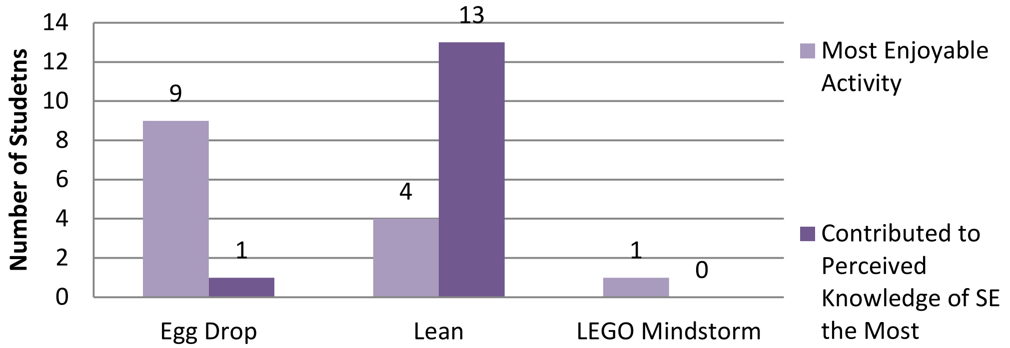

Figure 5. Activity Ratings by Students

The feedback on the LEGO Mindstorms challenge was interesting. The students were given a list of learning objectives and asked to rate them as very important, important, or not important to the different modules of the class. The learning objectives were:

- Enterprise Value/User Needs
- Design under operational uncertainty
- Rapid prototyping and learning for simple models
- Experience with integration, test and validation in simple systems
- Basic systems engineering tools and processes
- Value of upfront Systems Engineering: it's worth spending money early to save money down the road
- Balancing work across decomposed parts/value maps
- Design for manufacturability (relationships among parts of the process)

In Figure 6, the chart shows how the students rated the various objectives in terms of the LEGO Mindstorms Challenge. The main objectives the teaching team wished to convey through the challenge of integration, test and validation of simple systems and design under operational uncertainty are seen to be rated importantly which shows that the project did achieve the outlined objectives.

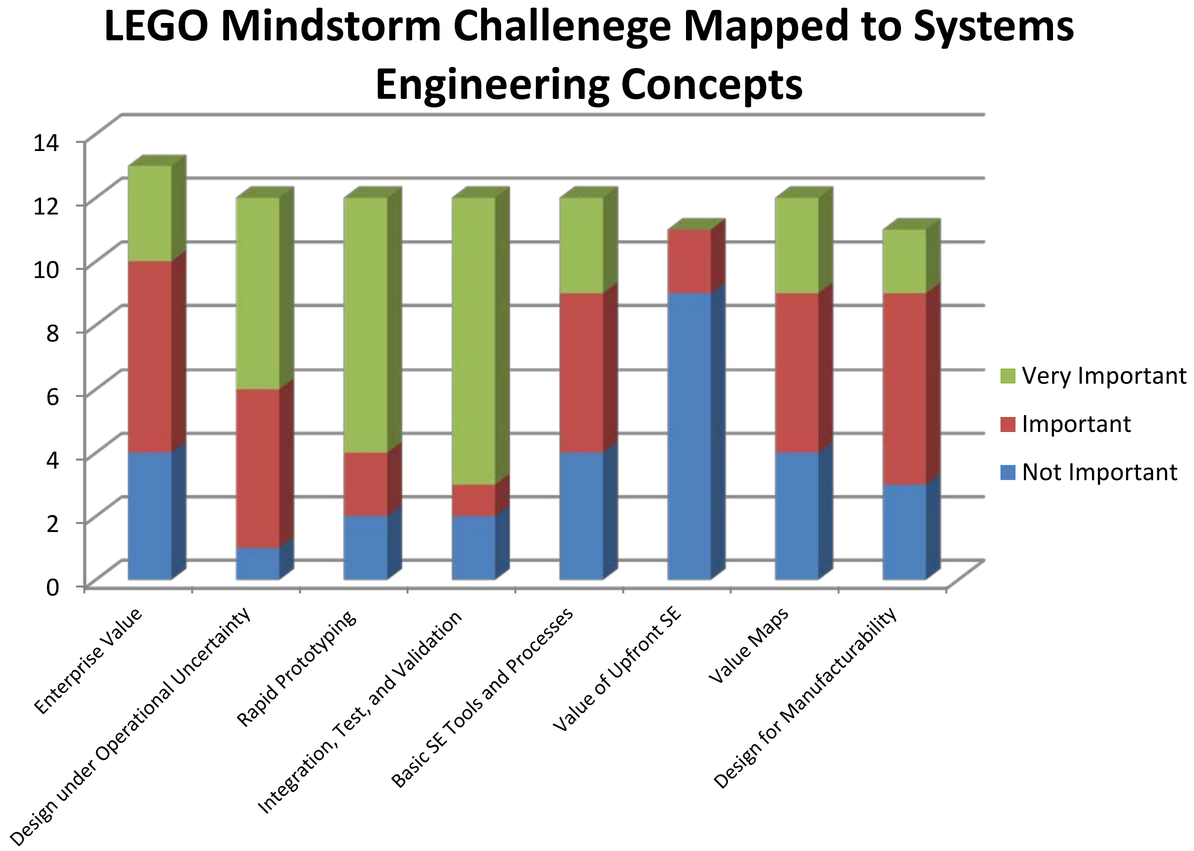

Figure 6. LEGO Mindstorms Challenge Mapped to Systems Engineering Concepts

VI. Conclusion/Lessons Learned

This paper has presented one approach to teaching Systems Engineering to first-semester freshmen. In developing the course, we had three main goals:

(1) Provide a context through which inexperienced students can value the discipline of Systems Engineering. One of the reasons why Systems Engineering is only beginning to gain popularity at the undergraduate level is that many practitioners believe that understanding of the technical system must precede the challenge of system decomposition and integration can be appreciated. To overcome this challenge, we selected practical projects that simplified the technical components (e.g., a LEGO airplane), but not the integration challenge. This allowed the focus of the learning experience to be on Systems Engineering processes.

(2) Develop a framework for the Systems Engineering curriculum that would follow. The next three years of their education will cover a wide range of tools courses, and without adequate background, they may seem independent. In designing the course, we picked a selection of projects that would motivate many of the process and tools courses that would be learned later. We hope that students will have a better framework for integrating the rest of their System Engineering education.

(3) Lastly, we hoped to guide the transition from high school coursework to the expectations of college level engineering. While this challenge is not unique to Systems Engineering, it is an important function of a freshman introductory class. The self-guided learning aspects of this course, was for many students, the first time that they had confronted instructors unwilling to provide them with answers. The teaching team was very conscious of the need to be available, but only as a sounding board. At first students were frustrated with being “left in the dark” but they rose to the challenge, and, by the end of the class were quite adept at trouble shooting problems as they came up.

As with any first offering of a course, there were aspects that warrant continued improvement. In future years we will likely change the pace of the Mindstorms check-ins to better monitor progress towards the goal. While the lack of success in the final challenge certainly reinforced core Systems Engineering lessons, we do want the class to end with a sense of accomplishment. We hope that other programs can learn from this experience, and that we can draw on each other’s lessons as the discipline continues to evolve.

References

1. O. Asbjornsen and R. Hamman, Towards a unified systems engineering education, IEEE Transaction on Systems, Man, and Cybernetics Part C: Applications and Review, Vol. 30, No. 2, 2000, 175-182.
2. W. Bauer, W. Biedermann, B. Helms, and M. Maurer, Student laboratory for Systems Engineering: teaching Systems Engineering to students without previous SE knowledge based on an industry-oriented example, 2012 International Systems Conference, IEEE Society, 2012, pp. 1-6.
3. C. Chittister and Y. Haimes, Harmonizing ABET Accreditation and the Certification of Systems Engineers, Systems Engineering, Vol. 14, No. 3, 2011, pp. 341-348.
4. A. Cruz-Martín, J. Fernández-Madrigal, C. Galindo, J. González-Jiménez, C. Stockmans-Daou, and J. Blanco-Claraco, A LEGO Mindstorms NXT approach for teaching at Data Acquisition, Control Systems Engineering and Real-Time Systems undergraduate courses, Computers and Education, v 59, n 3, 2012, pp 974-988.
5. S. Ferguson, H. Klumpe, and J. Turner, The incredible egg: Investigating the design education challenges and complexity of the egg drop project, Proceedings of the ASME Design Engineering Technical Conference, Vol. 6, ASME, 2010, pp. 647-659.
6. M. Frank and D. Elata, Developing the capacity for Engineering Systems thinking (CEST) of freshman engineering students, Systems Engineering, Vol. 8, No. 2, 2005, pp. 187-195.
7. M. Gorman, Turning students in to professionals, Journal of Engineering Education, Vol. 91, No. 3, 2002, pp. 327-331.
8. International Council on Systems Engineering, INCOSE List of SE Programs July 2013, https://www.incose.org/educationcareers/academicprogramdirectory.aspx.
9. C. Jalain - D. Lafore, J. Chevalier and S. Banguet, Teaching systems engineering: a multidisciplinary project based feed-back on a pedagogic experiment: "EasyKawa 2004" project, 2005 European Conference on Power Electronics and Applications, IEEE Society, 2005, pp. 1-9.L. Keys, Systems Engineering and Technology Management education for the 21st century, 2009 Portland International Conference on Management of Engineering and Technology, IEEE Society, 2009, pp. 2152-2170.M.
10. L. K. Keys. System Engineering and technology education in the 21st century. PICMET 2009 Proceedings, PICMET, 2009, pp. 2152-2170.
11. LEGO® education, http://www.legoeducation.us/eng/characteristics/ProductLine~LEGO%20MINDSTORMS%20Education%20NXT.
12. H. McManus, MIT Lean Advancement Initiative, http://lean.mit.edu/products/lean-enterprise-value-simulation-lev.
13. Mehta, Hands-on simulation to demonstrate key metrics for control of processes utilizing lean and six sigma principles, ASEE Annual Conference and Exposition, Conference Proceedings, ASEE, 2009.
14. National Aeronautics and Space Administration, Systems Engineering Handbook, December 2007, http://foiaelibrary.gsfc.nasa.gov/_assets/doclibBidder/tech_docs/5.%20NASA%20SP-6105%20Rev%201%20%28Sys%20Eng%20Handbook%29.pdf.
15. A. Sage, Systems Engineering education, IEEE Transaction on Systems, Man, and Cybernetics Part C: Applications and Review, Vol. 30, No. 2, 2000, 164-174.
16. K. Shimazu and Y. Ohkami, Systems Engineering education for inexperienced students by providing hands-on practices, 2011 International Systems Conference, IEEE Society, 2011, pp. 367-370.
17. T. Subramanian, Mukundlal, Prempyari, and P. Dubey, Systems Engineering: a new approach to engineering education in India, 2012 IEEE International Conference on Innovative Practices and Future Trends, IEEE Society, 2012, pp. 1-3.

Appendix A – Introduction to Systems Engineering Course Objectives

University	Focus of the Course
Auburn University	"Students will acquire an introduction to Industrial and Systems Engineering, accounting and engineering economics, optimization, simulation, probability and statistics, facility layout, quality control, safety, human factors, and ethics."
George Mason University	"Students will become familiar with common SE terms and procedures as well as terms and procedures of other engineering disciplines. Students will also learn to use CORE, a systems engineering software program."
Oakland University	"In order to satisfactorily complete this course, a student is expected to demonstrate competency concerning their understanding of the following objectives: • Describe the role of an Industrial Engineer in a manufacturing/service industry (j). • Understand the concept of population distribution and sample distribution (a, e). • Apply probability concepts of counting, mean, variance, expectation and others (a, e). • Apply discrete distributions including uniform, binomial, Poisson, geometric, and others (a, e). • Apply continuous distributions including uniform, normal, exponential, lognormal and others (a, e). • Estimate parameters with a given level of confidence (a, e). • Apply the concept of probability to real world problems (a, e). • Analyze data and estimate variation in a data set (a, b, e, k). • Apply probability and statistical operations on data using Excel (a, b, e, k)."
University of Alabama, Huntsville	"Development of a systems-scientific framework for the integration of systems theory, systems thinking, systems engineering and systems management. Emphasis is on the conception, design, and management of systems to accommodate complex environments."

University of Arizona	"This course is intended to give students background and a foundation in the design of systems. We will discuss the systems design process including: Requirements Development, Concept Development, System Architecture Definition, Trade-off Analysis, System Development, Testing, Deployment, and Project Management. We will concentrate on System Modeling, Analysis and Simulation, Performance Measures, Trade-off Studies, Design Optimization, and Project Management."
University of Arkansas at Little Rock	"1. Introduce students to on campus resources to enhance success and introduce students to the University's processes and expectations. 2. Introduce students to the engineering profession and creative engineering problem-solving through class activities, design projects, and presentations. 3. Familiarize students with the various engineering disciplines and their interrelationships. 4. Provide historical perspective on engineering design processes, successes, challenges, failures, and their influence on contemporary society. 5. Inspire and instill an appreciation for the engineering profession, its ethics, and practices. 6. Learn and apply engineering design process in proposing and building working devices or models that meet preset constraints and specifications. 7. Introduce students to communication, teaming, and project management skills necessary to excel in today's engineering workplace."
University of Southern California, Los Angeles	"• To improve the students' ability to ask the right questions and apply the right methods when architecting systems. • To improve the students' understanding of the role of system architects and their relationship to systems engineering. • To introduce the students to new and advanced topics relevant to complex systems architecting and modeling."

University of Virginia, Charlottesville	"1. Explain and effectively apply systemic thinking within a systematic approach to open-ended problems a. formulate a problem and develop a clear statement of needs • goals, objective trees, indices of performance • functional requirements and design specifications based upon system trades b. identify solutions to a problem • creativity and innovation, brainstorming, researching existing/near solutions to the same/similar problems c. evaluate and select solutions to a problem • assess what information is necessary information for evaluation (iterative and error embracing) • gather necessary information • apply modeling tools… see “systems modeling and basic analytical tools” below d. explain and apply iteration as needed both within steps and through an entire process 2. articulate their personal view of systems engineering methodology based on their experiences with applying systemic thinking within a systematic approach in a variety of contexts 3. explain and apply basic systems modeling and analytical tools, including introductions to • decision trees • multiattribute value theory, intro to utility theory • group/team decision making • fitting distributions to data (as applied in decision making, using software such as @risk) • montecarlo analysis (as applied in decision making, including sensitivity analysis, using software such as @risk) • engineering economic analysis • pre- and post- analysis work, including understanding the meaning of data, cleaning data, performing sensitivity analysis, and asking “do my results make sense” 4. communicate effectively with clients/stakeholders a. interact with stakeholders to formulate a problem b. create and deliver effective “client” presentations c. write effective technical documents for clients 5. work collaboratively on complex systems problems involving technology and multiple stakeholders "

Washington University in St. Louis	"The course consists of various modules that introduce the students to fundamental ideas and concepts from systems theory. The modules will be topic oriented, interdisciplinary units that describe underlying problems and show how system theoretic ideas and concepts are vital in the modeling and analysis of the problems. Topics for the modules will have both a local or micro and a global or macro aspect to it and come from various areas of science and engineering. They will include (i) classical control systems(e.g., flight control systems such as an auto-pilot, robotic manipulators, path planning,. . .), (iii) climate and environmental systems (local weather forecasts versus global warming), (ii) economic systems (individual investment decisions versus management of a country's economy, carbon trading), and if time permits (iv) biomedical systems (tumor development versus treatment approaches). Some of the topics juxtapose global and unsolved, potentially unsolvable problems against specific and fully understood components. Integration of local aspects into the global system will be discussed. Following the discussions of the modules in class, students are expected to research and present small projects from these areas. The topic modules will be complemented by interwoven lectures that give an introduction to the needed background on mathematical tools for the formation and analysis of models. These include (i) dynamics and differential equations, (ii) elements of matrix algebra and (iii) aspects of uncertainty (both deterministic and stochastic)."
San Jose State University, San Jose	"(1) Interpret the theoretical framework, methodological approaches, and contemporary development of any given system and improve it effectively and efficiently. (2) Assess the principles and concepts of system life cycle costing and relevant models for economic evaluation using quantitative and qualitative methods. (3) Design and develop a new, effective and efficient system. Achieving this goal requires the student to explain the existing theories, methods and tools that have been developed to help build a new system and identify their limitations. (4) Achieve an intellectual understanding of optimization and control concepts in systems operational feasibility. (5) Execute the methodology and tools of systems engineering"
University of Minnesota-Minneapolis	"This course is a basic introduction to important models and solution methods in Industrial and Systems Engineering (ISyE). ISyE is concerned with the modelling, analysis, and solution of complex decision problems that arise in the

	management or design of a large-scale industrial system such as a supply chain, transportation network, or manufacturing assembly line."
University of San Diego- San Diego	"Upon completion of the course you should be able to: 1. Explain the principles of the system development life cycle (SDLC) process and its role in the engineering enterprise. 2. Apply fundamental systems design and implementation techniques to the solution of practical engineering problems. 3. Explain the importance of model development in support of system design and system analysis 4. Explain importance of each stage of engineering development lifecycle 5. Develop understanding of system engineering management process 6. Develop structural and process models to generate and evaluate a range of system designs. 7. Generate and apply measures of effectiveness to compare competing system solutions. 8. Function effectively as part of a student team to achieve a realistic complex system design."
Youngstown State University	"This course introduces students to a systems philosophy of engineering problem-solving. Problems that arise within complex systems are illustrated through real-world examples and case studies. Students will be introduced to tools and terminology used to address a wide range of systems problems. Problem solving approaches requiring problem decomposition, implementation of solutions to sub-problems, and interfacing of sub-problem solutions in the context of the overall problem will be discussed. On successful completion of this course, the student shall be able to 1) employ a systems engineering approach to projects; 2) differentiate between problems that occur at the systems level versus those which occur at the solution or sub-solution level; 3) utilize appropriate tools and terminology to characterize systems-level problems; and 4) suggest appropriate strategies to reduce likelihood of systems failures."

Acknowledgements

We would like to thank the following schools for providing us with information about their Systems Engineering programs:

Auburn University

George Mason University

Georgia Institute of Technology

North Carolina A&T State University

Oakland University

Ohio State University

San Jose State University

Stanford University

Texas Tech University

University of Alabama, Huntsville

University of Arizona

University of Arkansas at Little Rock

University of Michigan – Dearborn

University of Minnesota

University of Pennsylvania

University of San Diego

University of Southern California

University of Virginia

Washington University in St. Louis

Youngstown State University