122nd ASEE Annual Conference & Exposition
June 14 - 17, 2015
Seattle, WA
Making Value for Society

Paper ID #12477

Outcomes of a Systems Engineering Project for K-12 Teachers

Prof. Greg Bartus, Stevens Institute of Technology

Greg is an Adjunct Teaching Professor and Senior Curriculum and Professional Development Specialist in STEM Education for the Center for Innovation in Engineering and Science Education at Stevens Institute of Technology. Greg has an MAT and BS in Agricultural and Biological Engineering from Cornell University.

Dr. Frank T Fisher, Stevens Institute of Technology (SES)

Frank T. Fisher is an Associate Professor in the Department of Mechanical Engineering and co-Director of the Nanotechnology Graduate Program (www.stevens.edu/nano) at Stevens. He has been awarded the NSF CAREER award, the ASEE Mechanics Division Ferdinand P. Beer and E. Russell Johnson Jr. Outstanding New Educator Award, and the 2009 Outstanding Teacher Award from the Stevens Alumni Association.

Outcomes of a Systems Engineering Project for K-12 Teachers

Introduction

President Obama's Educate to Innovate initiative set a goal of preparing 100,000 new and effective STEM teachers over the next decade.[(1)] Concurrently, the publication of the Next Generation Science Standards (NGSS), authored and published by Achieve, Inc. (2013), puts emphasis on crosscutting concepts (such as systems & systems models and energy flow) and science and engineering practices which has furthered a trend to make engineering explicit and integrated into the science curriculum in the United States.[(2)] This increased focus on STEM and engineering education has put the engineering process and scientific practices in the spotlight in education circles. The primary issue that arises is that educators are not ready to teach engineering experiences.[(3) (5)] Our goal was to mediate this issue by using a graduate systems engineering course to expose teachers to engineering experiences and to help prepare them to meet the Educate to Innovate initiative.

There are many curricula that provide an experience in component design for K-12 students and teachers where students are engaged to design simple to complex structures or processes.[(4)] However there are a couple of aspects that reduce the authenticity of such projects. First, the instructor often plays the role of the manager or engineering lead which makes the project easier to control and manipulate; unfortunately, this leading role takes decision making and autonomy away from the students. Second, a commonly taught aspect of engineering solutions is that there are many solutions to a problem; this is meant to reduce competition in the K-12 setting and allow all students the opportunity to succeed. However students may be unsatisfied at the end because of confusion over the measure of success, what the next step would be, and what completion looks and feels like. To address these concerns, we have explored the use of systems engineering to increase the authenticity of the engineering experience for students. Systems engineering encompasses component design within a framework that also enhances 21st century skills such as teamwork and collaboration through a higher degree of autonomy. Also, systems engineering provides another level of science and math, engineering involved in systems integration, and data analysis.

Methods

The students in this NSF-sponsored program are grades 3-8 classroom teachers from select school districts who are enrolled in a five course science and engineering content sequence to either become eligible for state science certification or enrich their current science background. Elementary teachers in the program typically have minimal science and engineering background while middle school teachers have some science background but little engineering experience.

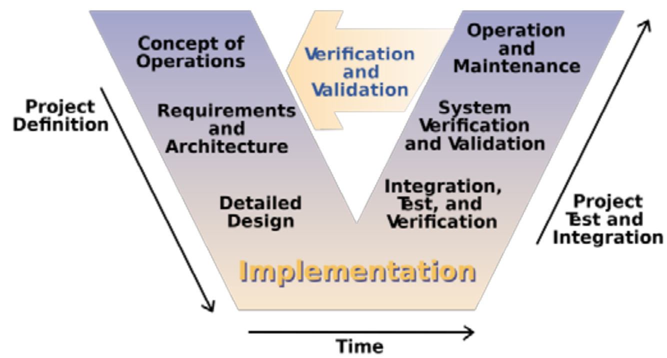
The course, Engineering Solutions to the Challenges of Energy and Global Change, examines the science principles supporting the engineering solutions pursued for issues related to energy production/consumption and climate change. Discussions from a systems perspective drive approaches being implemented to move toward a more sustainable world, including the development of grid-scale wind power as well as engineering solutions to reduce the effects of global change. A key component of the course is to have students design an operating wind farm that powers an electric grid in the context of a system-level design as part of an exhibit for a community science center. Designing the wind farm (vs. a solar farm) allowed students to apply electric circuit knowledge and skills similar to designing and building a generator. The blades offer another component that requires integration as well. The grid affords challenges in collection, storage and distribution of energy. Finally, an exposition model avoids any issues with scaling up and the abstraction it entails while making a final presentation a better culminating activity for demonstration of deep understanding with the context of a science center making explicit the need to support science and component engineering design behind the final solution.

Our goals for the Wind Farm project were threefold:

- Provide teachers with an authentic systems engineering experience which conveyed the challenges of system integration. In addition, we wanted them to experience the following systems engineering laws [9]:
    - In all phases, the systems engineer has to take into account: the customer's vision and goal.
    - The whole has to be seen as well as the interactions between the system's elements.
    - Always take into account electrical, mechanical and quality assurance considerations as well as environmental constraints.
- Provide teachers with an authentic component engineering design experience which conveyed the following engineering concepts: requirements, constraints, trade-offs, optimization, prototype.
- Encourage scientific and quantitative analysis during integration and optimization. As science teachers it is critical that the endeavor has relevance to their classroom and to understanding science better.

We started out by providing a project-specific Request-for-Proposals (RFP) (see Appendix 1.). The goal of our RFP is to define the problem and outline some of the project requirements. Students were also given a rubric to be used in evaluation (See Appendix 2.). To increase authenticity and align with university expectations, the evaluation rubric was based on Accreditation Board for Engineering and Technology (ABET) standards. We provided most of the equipment and materials that students would need including KidWind materials (www.kidwind.org), voltmeters, box fans, testing instrumentation, building materials.

Teams of ten were given sufficient class time to develop a final presentation for outside customers (educators with engineering and physics content knowledge). Teams selected the Systems Engineer (SE) and identified individual roles for focused attention on targeted components or subsystems. These subsystems primarily focused on blades, generator and the electric grid. Training was provided to the both teams in the following engineering concepts: constraints, requirements, trade-offs, optimization, and prototyping. The SEs were provided with more detailed training and resources such as the Vee model which they shared with the rest of their team. That being said, we wanted the students to experience systems engineering and component engineering first and reflect on the terminology later. Teams started out with two larger teams to kick off designing blades and generators and then later evolved into smaller groups with 2-3 'rovers' to assist on other tasks.



Instructors were available as advisors only. We felt that it would be more authentic to have evaluators come from outside the class so that we became part of the team and interested in their success. Partway through the process we intervened to hold mini-conferences for blades, generator, and electric grid and systems engineers. Specialized sub component 'experts' were given time to share what they were doing and what problems they were running into as a way of modeling scientific and engineering conferences.

At the end customers came in to see the presentations and students reflected on the following questions which we used in our analysis: What were your contributions to the project? What did you learn about the engineering design process and systems engineering? How might you incorporate an idea from your experience into your classroom?

Findings

Friedman and Sage recommend analysis of case studies in systems engineering via a two dimensional matrix outlined by the concept domains and responsibility domains.[8] Because of our goals, the second dimension covers science content knowledge and practices and engineering skills from the private sector viewpoint. As such we sacrificed inclusion of other complexities common to systems engineering such as public sector and non-profit organizational concerns. Still it is sensible to use this matrix for our qualitative analysis.

Project Decomposition

As one SE reflected, “Collectively we were immediately overwhelmed with the lack of experience and knowledge necessary to take on such a large task.” While that may have overstated their position, Frank and Elata [(6)] among others suggest that conceptualizing the ‘big picture’ is important and yet challenging for the initiate. Even though we took some measures to expedite and ameliorate the process, we did anticipate and desire some discomfort.

Concept domain	Science content and process	Engineering process skills
Project decomposition		
A. Requirements & Architecture		X
B. Subsystem design	X	X
Project integration		
C. Systems integration		X
D. Validation and verification		X
E. Deployment	X	X

A. Requirements and System Architecture

The analysis of the requirements is one critical element to systems engineering [(6)] but given the experience of our teams we provided scaffolding to help them synergize with systems engineering ideas. Thus we made some accommodations for systems decomposition such as explicit requirements in the RFP and subsystem definition and training. We could have opted for a more open start; however, these supports were intended to alleviate the earlier concerns and overcome our time constraint without sacrificing autonomy. Finally, some constructs already exist, such as turbine architecture, which made for a logical division.

B. System and Subsystem Detailed Design

This domain gives motivation for having two dimensions to our analysis to cover both engineering process and science content and process.

- Engineering process

The wind turbine offered clear subsystems that could be decomposed and tested; based on equipment and time constraints we focused on the blades and generator. We considered involving teams in the design of the gear box between the two but the modifications to the project and the time required were too great.

What we found is that the teams needed time to establish testing protocols as well as decide on testing variables. Blades were tested using a box fan, standard motor from Kidwind and a voltmeter. Generators were tested using an electric drill and voltmeter. These were suggested and discussed as techniques to manage control variables when they reach that point in their discussions. The process for the blades was described this way by one participant:

> Through my research I uncovered that wind turbines that include two to three blades, include a curved point, are light-weight, have a length relative to the wind source, and included a pitch of 20 degrees, achieve maximal results producing energy. My partners

> and I constructed over fifteen different blade designs out of various materials and we rotated the assembly of the blades onto our generator for testing.

Designing the generator involved a similar analysis of variables:

> We determined that we would need to gather data on the generator so we determined our variable for testing: smaller versus larger magnet, 150/ 200/ 250 copper coils per side of generator case, and gear ratio. We realized that gear ratio was pre-determined with the parts from the kit, so we focused data on number of coils of copper and magnet size, testing each and putting data in a table. We used a drill to mimic the spinning of the turbine, and a multimeter to measure voltage.

In both cases, they were proficient at testing and optimizing their designs with some challenges. The biggest limitation was collecting precision data for comparison. In particular controlling wind speed in testing blades generated some confounding results.

- Science content and process

Teams clearly applied concepts from studying electricity earlier in their course sequence to design the generator; especially knowledge of circuits, units of measure and Ohm's law. While they may not have an expert understanding they were expanding their model. As one participant describes the process:

> Everyone in our group feared 'the generator'---none of us knew what it was, how it worked, and where to begin. I realized the generator was a key component to the windmill, transferring mechanical energy into electricity. J and I volunteered to tackle this unknown component head on. We began by researching what a generator was and how it worked. We realized that as the blades spin they would be attached to a shaft that would drive the generator to spin. Inside the spinning generator was a magnet and surrounding the magnet was coils of copper wire. The turning of the magnet excites electrons that are then transferred into the copper coils and travel through the wire, an electrical current. The copper wire would then be attached to a capacitor to store electricity or to a load to provide electricity (LED lightbulb). We found that the larger magnet at 200 coils produced highest power output, which we calculated by taking voltage squared divided by 10 ohm for the resistor we used. We measured power in milliwatts since the output was so low.

Additionally the electric grid gave participants a chance to use physics knowledge. As one participant explained:

> I wanted to test both the parallel and series circuits using the same resistance (5 red LED lights and motor) to see which set up was most efficient. I set up both circuits to be

> powered by two AA batteries. The circuit that was set up in parallel had no problems lighting the entire circuit with the 3 volts provided by the two batteries. The circuit that was set up in series was unable to power the lights or the motor with 3 volts. When I shortened the circuit to one LED light, it was able to light it with no problem. When I added the second light into the circuit, the LED lights were barely visible. When a third light was added into the circuit, nothing was visible but there was still power running through the circuit according to the volt meter. The parallel circuit was clearly the best option for the wind farm design and went along with my predictions. In the series circuit there is only one path, the voltage load for each component adds up and has a cumulative effect. If one component goes out, the entire system does not work. In the parallel circuit there are many different paths, the largest load requirement of the components is what is required for the circuit. Also, since the parallel circuit has multiple paths, each branch is able to function independently of one another. I was able to put switches at each of these branches to demonstrate this effect. This feature also makes the parallel circuit more closely related to a real life grid. I envisioned each one of the branches with LED lights to be a neighborhood and the other components to be a heliport, radio station, and hospital.

The introduction of the capacitor further enhanced their prior understanding in part, perhaps, because conceptually it is easier to grasp than a rechargeable battery.

Though designing the blades could leverage forces and vector notions, we found that students made few connections in this respect. Our recommendation is to support explicit connections to these concepts in the mini-conference which will be a focus when the project is re-implemented in the next offering.

Project Integration

C. Systems and Interface Integration

What separates systems engineering from traditional engineering is the inclusion of systems thinking [(11)] which the decomposition and integration aspects capture. Furthermore, the integration aspect captures the misconception of, as Beasley and Partridge describe, "trying to make the best parts rather than the best system - and so not recognizing 'the whole is greater than the sum of its parts'". [(11)]

Here we learned valuable lessons regarding system integration, a documented problematic phase in real world organizations because several strategies exist. [(10)] First, this was clearly the aspect that offered the greatest trouble to each team. Teachers had some relevant science and math knowledge which could be applied to the components. However, we found they were not skilled or experienced enough to respond to, or anticipate, integration obstacles. Thus the designs that were optimized during testing were not necessarily successful when integrated into the wind turbine. Second, we observed that a lack of efficacy in component testing mixed with external (time) constraints led to a more trial and error approach once these obstacles were encountered.

> We were hoping to find that a larger magnet would also show more energy but with the size of the generator casing that we had to work with, this became a constraint. Because there were more coils and a larger magnet, the generator was too difficult to fit onto the windmill stand and remain stable. Also, because a larger magnet would require more torque to turn it, we would need to use a larger gear to turn the blade gear; a lower gear ratio would work for this but we were limited with the gears we had to work and mostly we were limited with time. We would of course need more time to find ways to work around this new problem. We settled on using the smaller magnet with more coils; enough coils to still fit into the windmill stand and remain stable.

In 'going back to the drawing board' many of the good habits they were learning started to decay and testing focused more on 'jumping to the solution' [7] and initial ideas were favored even though it may have lacked a strong foundation.

While real world organizations are challenged by a choice of strategy, our students did not have the vision to recognize different strategies and approached it more as trial and error.

D. Validation and Verification

As the project progressed we found participants did not hold tightly to the subsystem teams to which they were initially assigned. They demonstrated what Beasley and Partridge [11] call tailoring in that they moved easily to other groups to complete more important tasks. As one participant stated,

> We then began working with L and R to build the final windmills with generators and set up the farm. We also worked with K to connect all generator wires into the grid she created. Once everything was set up we began charging the capacitor. At this point, I began working on power point slides for the generator and preparing our presentation. On presentation day, my job was to be the group's expert on building a generator and how the generator works. I also discussed why we chose the optimal design and restraints that effected our final generator decision.

As further demonstration, small teams investigated calculations for economics and efficiency for their turbines in relation to scale models.

> During the online week, I researched other Science museums on the Eastern Seaboard that currently are employing the use of some kind of wind turbine. Then, I priced a 10 kW wind turbine, since that is the size both museums are using as well as what size of a footprint a fictional museum in the city of Hoboken might require. Once I determined the size of the turbine, I could then calculate the cost per kWh from the 10 kW turbine versus the rate found on a PSE&G bill for Hoboken. I was able to calculate the pay back period

for the 10 kW turbine using the latest federal incentives and tax credits to reduce the overall cost.

Others demonstrated similar flexibility. Perhaps because they are classroom teachers they are more accustomed to seeing the ‘big picture’ or that they had been working together for a couple of summers, but in any case we found they worked well as a team to accomplish their goals. It may be that in an authentic systems engineering project, roles are defined by titles and organizations that make crossing boundaries challenging but also, this project was free of political or other external factors that might otherwise exist.

E. Deployment

The two teams had different interpretations of the customer or audience which influenced how the teams approached the designs. One team created an exhibit for use in the science center whereas the second team used a demonstration model to represent a scalable windmill designed for actual placement in the local area. Given the RFP, either approach is suitable however we recommend advising the customer to be prepared for different interpretations.

- Engineering process skills

We found that one of the presentations illustrated the engineering process well as they essentially walked through the systems engineering phases. This made for an effective technique for communicating their process. Both groups illustrated aspects of the systems engineering process in presentation.

- Science content and process

The RFP was designed so that in presentation participants would be prepared to demonstrate understanding of the science behind their system. As stated before, we found the science behind the blade designs did not manifest while the electric circuits, especially, were made clear.

“After our team’s final presentation, we all wanted to high five! This is the essence of what I would like to bring back to my classroom. The wind farm project had a balance of frustration and success.”

Conclusions

This case study presents our approach and the lessons learned from our experiences. While we found that the initial approach was successful we plan to improve the integration process and enhance systems engineering concepts.

First, as classroom teachers, they reflected an ability to recognize some engineering systems thinking skills such as systems (or circular or holistic) thinking in managing the project and valuing the customer. Furthermore, feedback from the teachers suggests that this will impact their classroom teaching; first, by replicating this project, but also by applying systems engineering to other projects such as aquaponics and solar houses.

> Being a Special Education Teacher, I typically do not permit such freedom in experiments. But, what I've learned though this process is that this type of freedom is essential in the engineering process. It has challenged me to reconsider the way I scaffold in concepts in the classroom. Although I am aware of how my typical students tend to "shut down" when an answer or a process isn't clear, I also now realize that the process of discovering the right path on their own is so important to the engineering process.
>
> I learned a great deal about the engineering design process. Prior to this class I truly thought it was a mythical concept. The engineering design process just happened, it had no terminology and no way for me to teach it in class. I am thrilled to say that all of this has changed since finishing the wind farm project!

Lastly, we want to achieve a balance during system integration between easy success and 'jumping to the solution' to optimize time and leverage systems engineering as a pedagogical approach. Perhaps embedded here is an important takeaway-- that engaging learners is analogical to a surfer riding a wave. We do not want our students to get too far ahead or behind the wave and yet the system is dynamic with the students providing feedback to the system and so there is no recipe for an ideal journey.

References

(1) http://www.whitehouse.gov/issues/education/k-12/educate-innovate

(2) NGSS Lead States. 2013. *Next Generation Science Standards: For States, By State*s. Washington, DC: The National Academies Press.

(3) Yasar, S., Baker, D., Robinson-Kurpius, S., Krause, S., Roberts, C. 2006. *Development of a Survey to Assess K-12 Teachers' Perceptions of Engineers and Familiarity with Teaching Design, Engineering, and Technology*. Journal of Engineering Education.

(4) www.teachengineering.org, www.tryengineering.org

(5) Brophy, S., Klein, S., Portsmore, M., Rogers, C. 2008. *Advancing Engineering Education in P-12 Classrooms*. Journal of Engineering Education.

(6) Frank, M., Elata, D. 2005. *Developing the Capacity for Engineering Systems Thinking (CEST) of Freshman Engineering Students*. Systems Engineering Vol 8 No 2.

(7) Dunford, C.N., Yearworth, M., York, D.M., Godfrey, P. 2013. *A View Of Systems Practice: Enabling Quality in Design*. Systems Engineering Vol 16 No 2.

(8) Friedman, G., Sage, A. 2004. *Case Studies of Systems Engineering and Management in Systems Acquisition*. Systems Engineering Vol 7 No 1.

(9) Frank, M., 2000, Engineering Systems Thinking and Systems Thinking, Systems Engineering VOl 3 No 3.

(10) Frank, M., Harel, A., Orion, U. 2014. *Choosing the Appropriate Integration Approach in Systems Projects*. Systems Engineering Vol 17 No 2.

(11) Beasley, R., Partridge R. 2011. *The three T's of systems engineering–trading, tailoring, and thinking*. 21st Annual Symposium of the International Council on Systems Engineering (INCOSE). Denver, CO, USA. Vol. 20.

Appendix

1. RFP

To whom it may concern:

The Hoboken Science Center is a place for people to go and learn about science and technology. We often are in need of new exhibits to engage visitors and we would like to have an exhibit that illustrates the value of alternative energy such as wind power. Therefore, we are looking for proposals from engineering teams which offer an optimized model wind farm with supporting data.

Aside from the system requirements below we are looking for a presentation that is innovative and illustrates the engineering design process so the wind farm should not only be operational but also show supporting data on how it was optimized so that we can share this process with visitors. Additionally, our visitors and some of our staff are not familiar with the science involved in some of the components so we may have questions on how they work so that we can share that information with visitors.

Our other System Requirements include:

- Wind farm using available materials is integrated into a grid
- Electrical grid has storage capacity
- Electrical grid has a load (LED lights, water pump, etc.) which represents a city
- System optimizes power output with available materials and can show evidence of testing and analysis
- Economic analysis of wind farms
- Team members have knowledge about the science behind the components (generator, blades, capacitor…) and the system (electrical grid) itself

Finally, the process will be competitive and we highly encourage innovative ideas. We will look forward to viewing final presentations on July 24, 2014.

Thank you for your time.

Wendy Day
Director, "Hoboken Science Center"

2. **Evaluation Rubric**

Criteria for Design Team Presentation	**3**	**2**	**1**
ABET Criterion 3(a) an ability to apply knowledge of mathematics, science, and engineering *How are decisions made in the project?* *What justifications are presented for choosing different alternatives?* *What explanations are given for justifications and decisions?*	Exceed expectations in ability to apply science, math and engineering knowledge to project. Clear, high-level scientific reasoning is used to justify decision-making.	Demonstrated ability to apply science, math and engineering knowledge to project. Many decisions made using scientific reasoning.	Demonstrated lack of application of science, math and engineering to project. Scientific reasoning is not as emphasized as trial and error.
ABET Criterion 3(b) an ability to design and conduct experiments, as well as to analyze and interpret data *What/How many variables are researched in each subsystem?* *How well are design variables researched?* *What data/evidence are used to make decisions?*	Exceed expectations to conduct effective research to make reasoned design choices in the project. Excellent use of control variables; data that show clear results; procedures well detailed.	Demonstrated ability to conduct effective research to make reasoned design choices in the project. Good use of experimental procedures with some weaknesses.	Demonstrated lack of application or ability in using research to make reasoned design choices in the project. Experimental design not well thought out; appears more trial and error.
ABET Criterion 3(c) an ability to design a system, component, or process to meet desired needs *How well does the presentation meet the desired needs and requirements of the customer?*	Exceed expectations to meet desired needs of the customer by anticipating problems or highlighting added features.	Demonstrated ability to meet desired needs and requirements of the customer.	Did not demonstrate an inability to meet the customer's needs or highlighted some weak areas or neglected some aspects of the customer's needs or requirements.
ABET Criterion 3(d) an ability to function on multi-disciplinary teams *How well do team members take initiative?* *How well does the team work together in setting up the final presentation and deal with last minute problems?* *Did everyone come prepared?*	Exceed expectations to work together as a team. Individuals showed initiative; everyone clearly contributed in setting up, presenting and problem solving	Worked well together as a team.	Teamwork not clear. Project appears to be run by one or two people; others did not pitch in to set up or solve problems.

ABET Criterion 3(e) an ability to identify, formulate, and solve engineering problems *How well were subsystem interactions dealt with?* *What problems arose and how were they handled?*	Problem solving was handled effortlessly. Problems arose in development or on presentation day and they were handled by the team with very few issues.	Problem solving was handled with few problems. Problems arose in development or on presentation day; some were handled well and others created temporary issues or setbacks.	Problem solving either not handled well or not discussed. Problems arose on presentation day but the team demonstrated difficulty in fielding them.
ABET Criterion 3(g) an ability to communicate effectively *How clear and cohesive is the presentation/project?*	The presentation was very cohesive, communicated clearly and all project demonstrations were very effective.	The presentation was cohesive, communicated clearly.	The presentation was not cohesive or was not communicated clearly.