Introducing Systems Competencies During Undergraduate Design

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A faculty team (professors of professional communication, mechanical engineering, and physics) at Rose-Hulman Institute of Technology have collaboratively designed and taught an intensive multidisciplinary design program in which undergraduate engineering and science students tackled one of the National Academy of Engineering's Grand Challenges [1] during a 12 credit hour 10 week summer program. The program is centered around designing a system to utilize solar energy for use in a less developed country [2] with major components of systems engineering integrated throughout the experience in the form of practice of model-based systems competencies [3]. For instance, students were required to identify stakeholders and analyze their needs via the development of feature models. In addition, the students were required to generate system domain models, feature definitions and attributes, and system logical and physical architectures. Each of these different types of models is discussed in the paper. In addition, we will discuss the relative degree of success students experienced with each of the system competency areas and our experience with integrating them into the classroom.

Course structure

The 10 week summer grand challenge course at Rose-Hulman Institute of Technology was structured around the National Academy of Engineering's Grand Challenges [1] in which students designed a solar energy device to benefit people in less developed countries such as Kenya. While participating in the course, the students earned 12 credit hours (4-science elective, 4-technical communications, and 4-engineering elective). [2] Ten total students participated in the program with majors ranging from physics to engineering. The program was expected to be especially popular among a large and growing number of students who want to explore the social contributions they can make as scientists, engineers, and emerging entrepreneurs. Secondarily, the program was intended to help improve retention by providing struggling students with hands-on learning opportunities. At the beginning of the course, the class was split into three teams who were tasked with developing a problem statement focused on making solar energy cheaper as well as locally manufacturable in a third world country such as Kenya. After an intensive problem definition phase, students determined a target location and defined the needs of local customers, which influenced the type of design proposed. For instance, one student group decided to focus on reducing malaria in Kenya, another group decided to focus on solving lighting needs, and the third group focused on providing clean water. The groups of students were free to change and develop their products through the design phase, and the systems engineering design methodology was intended to help steer the students to a successful design. At the midterm of the course, the class decided to continue to work on providing clean water, and students were reassigned into collaborative subsystem groups, each building a component of the final product and developing system artifacts at their discretion. Throughout this paper, student work is assessed to determine their success in using and understanding system competencies.

The system competencies as developed in Schindel et. al [3] lists a set of key concepts that a student should develop in terms of systems engineering. These competencies are:

1. Describing the target of innovation from a **systems perspective**;
2. Applying a **system stakeholder view** of value, trade-offs, and optimization;

3. Understanding system's **interactions and states** (modes);
4. Specifying system **technical requirements**;
5. Creating and analyzing **high level design**;
6. Assessing solution **feasibility, consistency, and completeness**;
7. Performing system **failure mode and risk analysis**;
8. Planning system **families, platforms, and product lines**;
9. Understanding **roles and interdependencies across the innovation process**.

Within the summer grand challenge program only a subset of these system competencies have been introduced.

The framework for the system's competencies aspect of the course included utilization of a systems engineering approach as described by the S*-metamodel (shown in Figure 1)[4]. The model based systems engineering approach, attempts to produce a number of "models" which map key features to both customer and other stakeholder desires, while also linking these key features to functional interactions of the system with its environment, thus providing more direct concrete methods for students to demonstrate systems competencies that typically take decades of professional experience to develop.

The goal of integrating model-based systems engineering (MBSE) into undergraduate education is to have more explicit framework for students to develop a product in which stakeholder needs are at the forefront. In addition, this framework forces the students to think about interactions that their product can have with the surrounding environment, thus allowing for students to consider the design before fabrication and reduce the possibilities of product failure by considering them early in the design process.

The components of the S*-metamodel that were focused in the Summer Grand Challenge Program included: stakeholders & features, domain models, logical and physical architectures, and state models. Table 1 provides the definitions of key terms used throughout this paper. For more information regarding system competencies see reference [2].

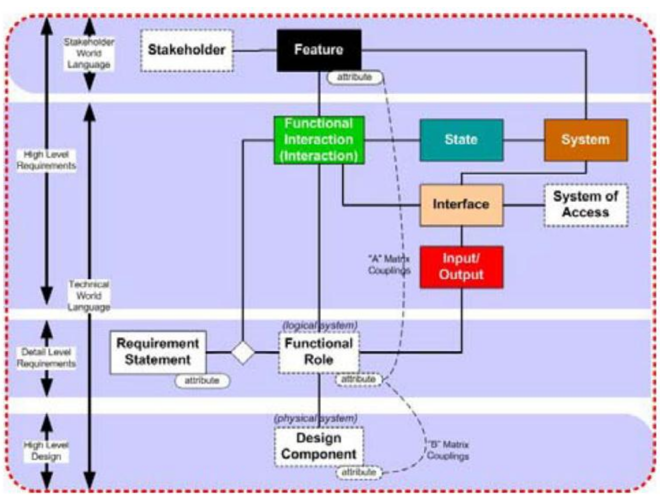


Figure 1 – Schematic of models comprising a version of the S*-metamodel [2].

Table 1 -Key terms and definitions of systems engineering

Term	Definition
System	A collection of interacting components
Component	A part of a system capable of interacting with other components
Stakeholder	A person or organization impacted by the proposed design solution
Environment	A system's surroundings, with which it has external interactions
Functional Interaction	Two or more entities exchanging energy, force, mass, or information, impacting each other's states
Feature	A collection of interactions that has stakeholder value
Domain Model	A diagram that describes the system's interactions with the environment
State Model	Different states, modes, or conditions that a system undertakes with corresponding functional interactions that are required during such states, and indicating the events marking transitions between them.
Logical System	A system identified solely by its externally viewable behavior or responsibility
Physical System	A system identified solely by its physical make-up
Functional Role	A behavior description of a part played by a system in a functional interaction
Requirements	External behavior a system must provide during functional interactions, without regard to how this is accomplished internal to the system.

Stakeholders and features

A key component to any design is to identify major stakeholders that are impacted by the contemplated innovation. The goal of determining stakeholders and features simultaneously is to help students understand key features that each stakeholder values and to see if any of the features are conflicting. Table 2 shows the stakeholders and features developed from a student team that was interested in providing clean water to a local tribe in Kenya.

Table 3 assesses student work in terms of the stakeholder and feature attributes seen in Table 2. The students were able to recognize several key stakeholders ranging from the local tribe to humanitarian organizations with relative ease. Thus, the students considered the main classes of stakeholders including people at risk of harm, owner, operators, maintainers, customers, and shareholders (not a stakeholder in this case as the goal was a not for profit product). It is interesting to note that the students considered domestic animals and wild animals as stakeholders, whereas typically only people are considered. In terms of features identified, the students developed a relatively complete set of features; however, they are missing replacability and repairability, both of which would be of interest to the maintainer and the installer of the product. In terms of mapping the features with the relevant stakeholders, the students in general correctly identified which stakeholder valued which feature. However, there were a few features that were specified incorrectly. For instance, the maintainer would not care about the visual appeal of the product.

Table 2-Stakeholder and feature model for water pasteurization group

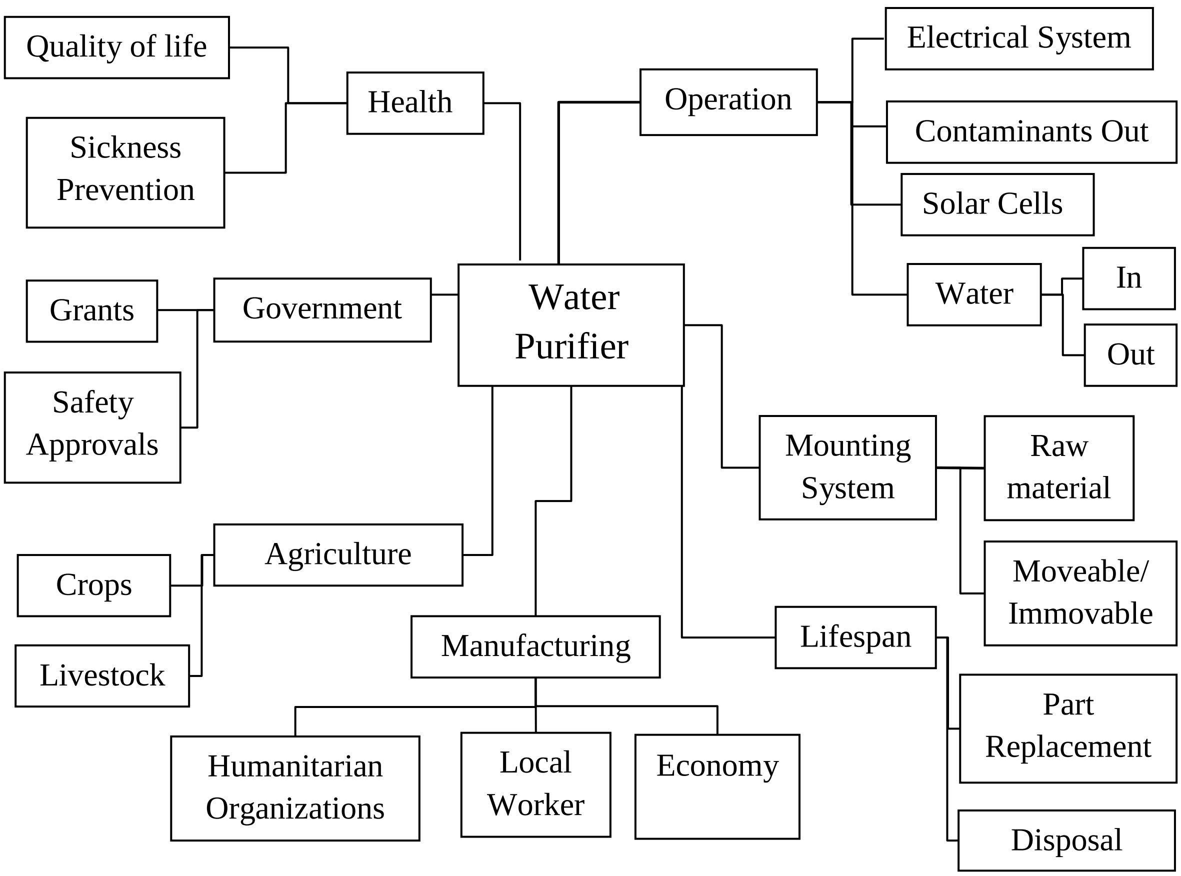
STAKEHOLDERS	FEATURES & ATTRIBUTES	MAPPING
1. Current water suppliers	a. Efficiency	1. a,b,c,d,e,f,g,h,i,m,n,o
2. Domestic Animals	b. Hours of operation	2. g,i,o
3. Entrepreneurs	c. Lifetime	3. a,c,d,e,f,g,h,i,j,m,n,o
4. Farmers	d. Local Manufacturability	4. b,c,e,g,h,i,j,m,n,o
5. Hospital staff	e. Price	5. a,b,c,e,g,h,i,k,m,o
6. Humanitarian organization	f. Product cost	6. b,c,d,e,f,g,h,i,j,k,l,m,n,o
7. Installation personnel	g. Quality of purification	7. c,d,i,j,l
8. Luo Culture	h. Reliability	8. d,j,k,m,n
9. Luo people	i. Safety	9. b,c,d,e,g,h,i,j,k,
10. Maintenance personnel	j. Size/portability	10. a,b,c,d,g,h,i,n,o
11. Masai government	k. Sustainability	11. a,c,d,e,f,g,h,i,k,l,n,o
12. Other locals	l. Type of power input	12. b,c,d,e,g,h,i,j,k,
13. Pastoralists	m. User-friendliness	13. b,c,d,e,g,h,i,j,m,n,o
14. Product designers	n. Visual Appeal	14. a,b,c,d,e,f,g,h,i,j,k,l,m,n,o
15. Students	o. Water Yield	15. b,c,e,g,h,i,m,n,o
16. Teachers		16. b,c,e,g,h,i,m,n,o
17. Tourists		17. a,b,d,g,h,i,n
18. Wild Animals		18. g,i,o

Table 3-Rubric used to assess students stakeholder and feature attributes

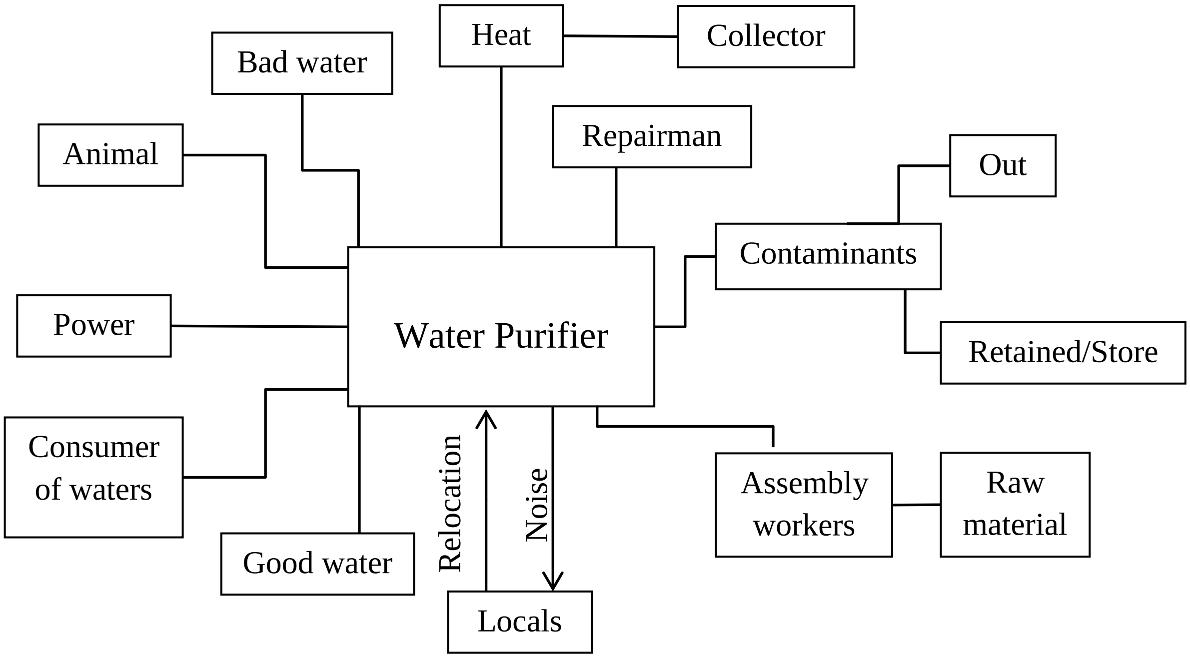
Criteria description	Percentage Met
What percent of the total set of classes of stakeholders in this system are represented by the stakeholder model?	100%
What percent of the total set of stakeholder interests are covered by the features and their attributes?	90%
What percentage of features are properly identified with each stakeholder class (i.e. association trace is available, showing which features are of interest to each stakeholder class).	90%

Domain model

Next, a domain model was developed that describes the system's interactions with the environment. Figure 2a shows the original domain model a student group developed, who were working on designing a water pasteurization system. Originally the domain model contained features and a few stakeholders rather than interactions with the environment. For instance, manufacturing and lifespan are features whereas government is a stakeholder who doesn't interact with the system directly.



(a)



(b)

Figure 2-a) Original and b) final domain model developed by student team who were developing a product to provide clean water.

After further explanation of the description of an environmental interaction, the students revised the domain model and focused more on physical interactions (Figure 2b). In the new domain model, the students primarily focused on entities that interface directly with the product. For instance, the students have both "good" and "bad" water interacting with the water purifier.

Table 4 - Rubric for Domain Model

Criteria description	Percentage met
What percent of external domain actors are identified by the domain diagram showing that the subject system is understood to be itself part of a larger system	80%

The students still did not identify flow directions and they missed environmental interactions. If the water pasteurization system is located outside, it must withstand the elements. For instance, wind and rain could cause potential issues especially during the rainy season in Kenya. The students also neglected to show a mounting interface, which seems to suggest that the device is floating in space, which is obviously not what the students intended.

Logical and physical architectures

A logical architecture partitions (decomposes) a system's externally viewable behavior; whereas, a physical architecture identifies a system solely by its physical make-up. In the beginning stages of model development, the students chose to represent both a physical and logical architectures simultaneously or concurrently. The pitfall with this technique is both the physical architecture and logical architecture are extremely coupled to each other such that it is difficult to imagine a plausible physical means that could possibly achieve two features simultaneously. Thus, the students were having difficulty with creating integrated designs. Therefore, we encouraged the students to develop a separate logical and physical architecture which are shown in Figure 3 and Figure 4, respectively.

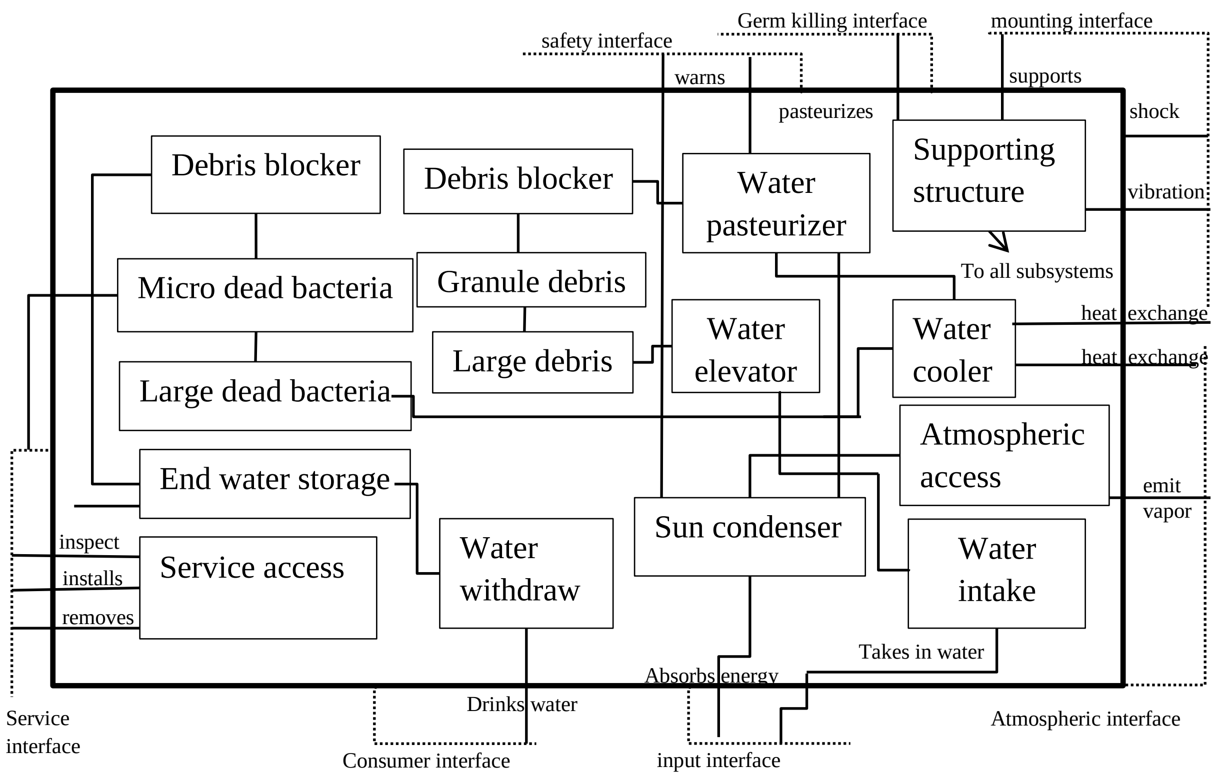


Figure 3-Logical architecture from a student team who decided to develop a product that purifies water.

Throughout the course the students became more comfortable developing logical architectures. As can be seen, the model is relatively complex for 2nd year students. Water is taken into the system, undergoes a series of filtrations, and is then pasteurized. After pasteurization, the water is again filtered followed by storage and eventual water withdrawal. In the model, individual components had descriptions that were general, allowing for numerous methods to perform the expected function, rather than linked to a specific physical object. The logical architecture not only included the system's externally viewable behavior but also included external interactions at the interface; however, it is interesting to note that environmental interactions such as wind and rain are still missing. It appears that the students are only considering how their system affects its surroundings but not how the surroundings can affect the system. The students did, however, recognize the need for a mounting interface, which wasn't included in the domain diagram.

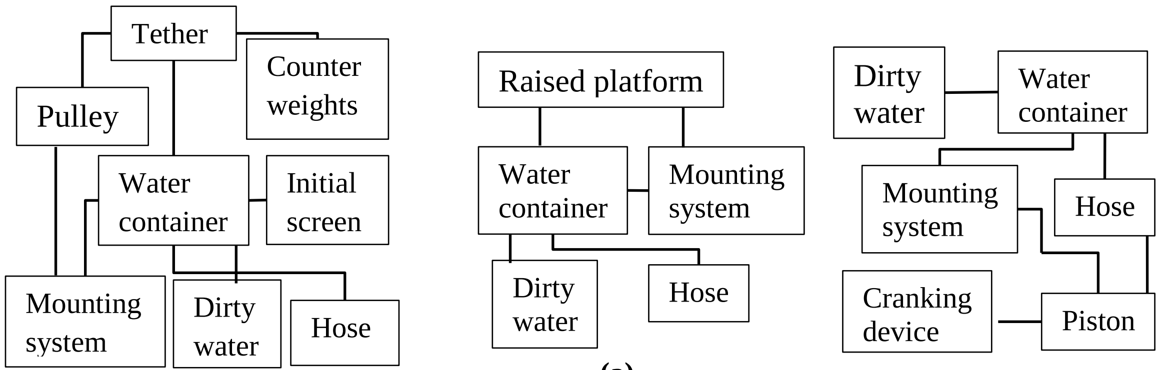
Table 5 -Rubric for the Logical Architecture

Criteria description	Percentage met
Logical architecture diagram is available, showing that the subject system's external behavior is understood to emerge from the interactions of a set of decomposed subsystems.	70%
What percent of the subject system's external behavior is covered by the logical subsystems / logical architecture model?	60%

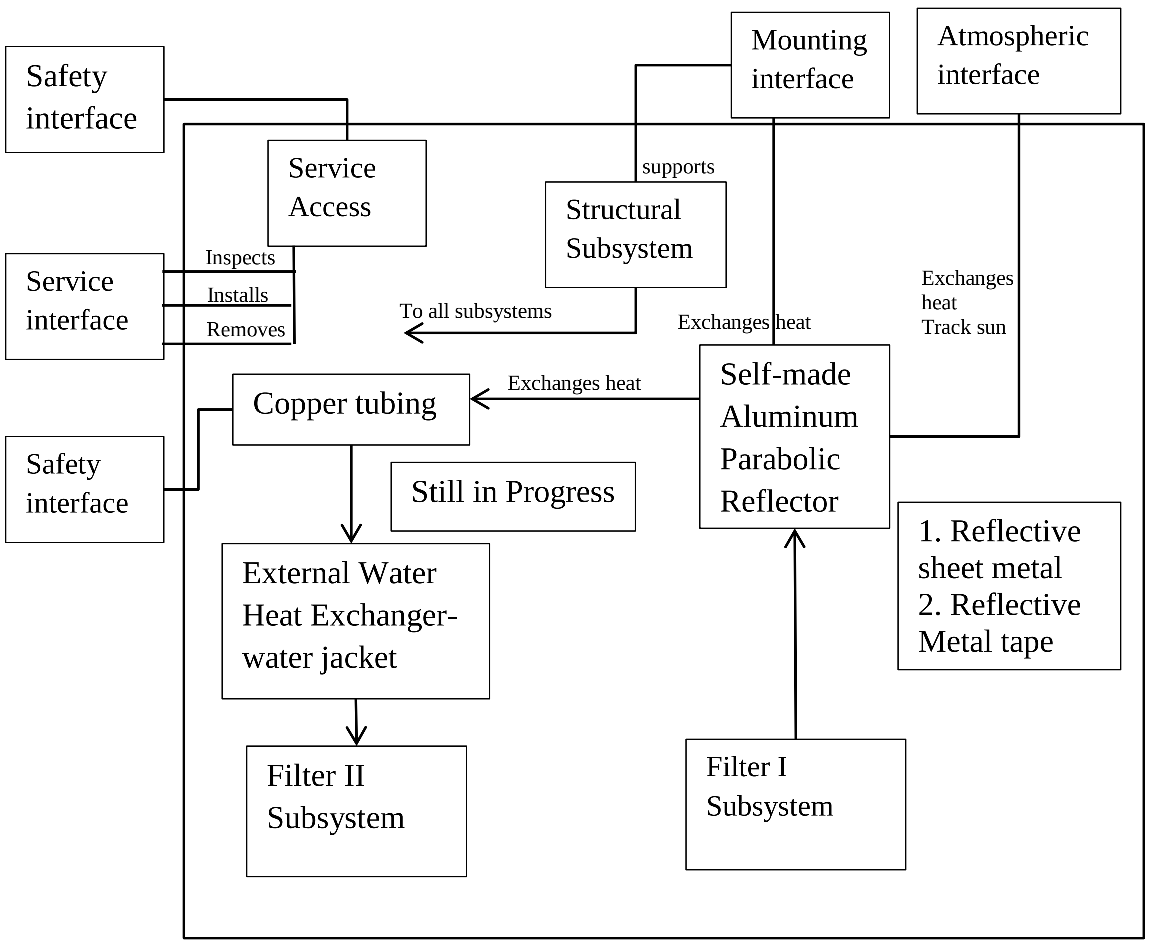
The students were able to generate a logical architecture that provided most of the functionality expected from their device. The challenges for the students were in the unwanted interactions the system may have with the environment, or subsystems with each other. For example, wind, corrosion, dust or other effects they may encounter from their environment.

In Figure 4a the "Water Lifting" subcomponent group, who were responsible for delivering dirty water to the pasteurization group, developed three unique physical architectures for their subcomponent design. Ultimately the design they selected to build was the simplest design as they felt the need for manufacturability trumped that of ease-of-use.

Figure 4b shows the physical architecture model for the heating subsystem group. As can be seen, the students are considering using a parabolic reflector to heat the water. Within the model, the students also identify other system teams such as the filtration group and structural group.



(a)



(b)

Figure 4-Physical architecture of a student subcomponent group responsible for (a) lifting the water and (b) pasteurizing the water.

Table 6- Rubric for Physical Architecture

Criteria description	Percentage met
A physical architecture model is provided, identifying and defining physical subsystems or components and their arrangement into physical relationships with each other.	60%
Key attributes (parameters) of the physical architecture are identified and defined.	30%

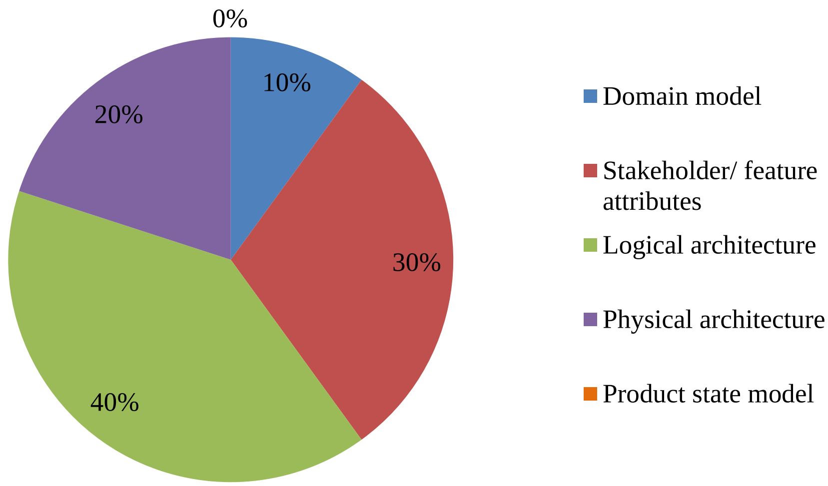
For the student group working on “lifting water” they continue to suffer from a difficulty in describing logical components versus physical components. For example, the students generalized a “mounting system” rather than describing in detail what components are required. In addition, no information is provided regarding human interactions (i.e. how are the systems powered). Also the flows to and from components are missing as to whether force, energy, mass, or information is being exchanged.

For the student group working on pasteurization, they considered the behaviors for their specific subsystem components such as the requirement of heat being supplied; however, the water entering and exiting the system isn’t shown in the diagram. In addition, they recognize structural support but the “how” is missing. For instance, detail regarding copper tube’s support within the parabolic trough is lacking.

Students perceptions of systems engineering

At the end of the course, the students were asked to fill-out a survey that contained questions regarding system competencies. Below are aggregated results regarding which models the students felt were the most and least useful (Figure 5). As can be seen, the students found the logical architecture the most useful, and we believe that this is because the model requires the students to think about how their device would function with little detail regarding what was its physical appearance. An extremely vital component to a device’s success is what it is capable of achieving. The students also found the stakeholder/feature attributes model valuable. This could possibly be due to the fact that stakeholders and features were previously discussed in freshman design. Thus, the students had already seen the material previously and could have thought that since the material is taught during a required course that it must be important. The students found the state model the least useful. This could be due to the fact that we didn’t spend much time discussing or developing this model.

a) What systems engineering model do you find most useful?



b) What system's engineering model do you find least useful?

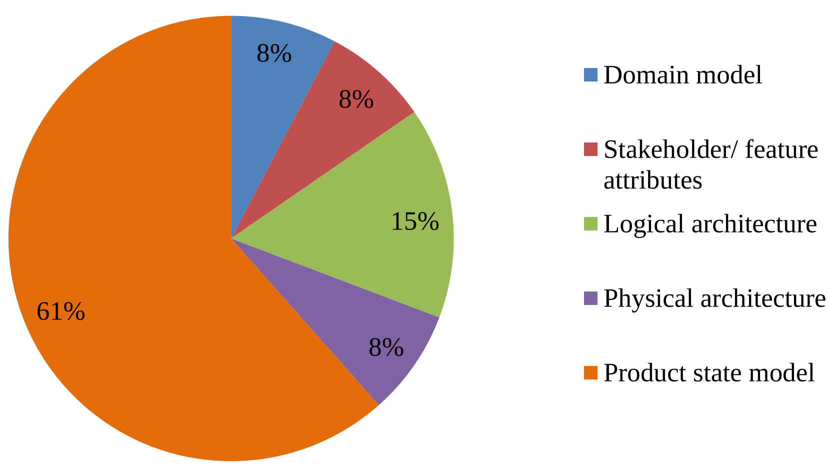


Figure 5-Student responses regarding a) the most useful and b) the least useful system engineering model developed during the class.

In addition to asking students about the usefulness of different models, we also asked them what order they would use systems engineering models to develop their design (Figure 6). Not surprisingly, the students simply regurgitated the exact same order in which we presented the models during class. The approach should truly be iterative. Models should be updated as more information is learned about the system as the product is developed.

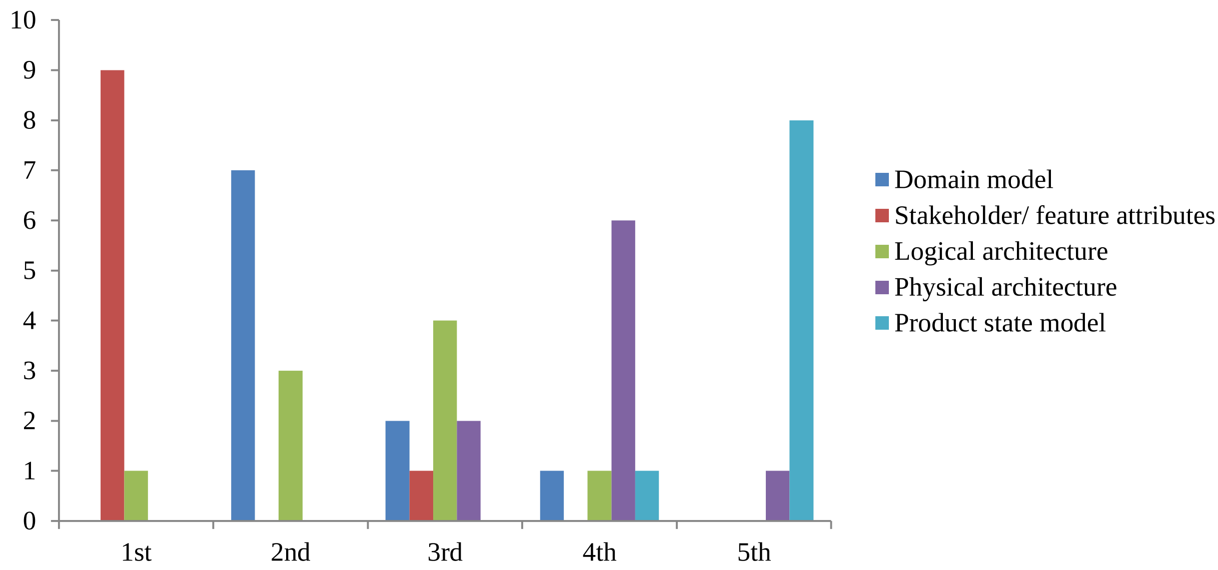


Figure 6-Student response regarding what order the system engineering models should be developed.

Conclusions from student work

Two main issues that the students were having when creating their system's models were considering cultural aspects of the geographic region where the product would be implemented early in the design process and using the models to actually influence their design choices. A large focus for the course was placed on fabricating a device using locally available supplies. One group repurposed soda cans into a stirling engine as these are ubiquitous in the United States, however, it is interesting to note that soda cans in Kenya are rare as nearly all soda is supplied in glass bottles. The students didn't even think to consider cultural variation in packaging of products. In general, all student teams lacked the consideration of cultural aspects of the design. Even the pasteurization group assumed products readily available in building supply stores in the United States would be readily available in Kenya. In addition, once a model was graded, the students rarely used the model to influence design decisions. For instance, one of the key states that the students recognized for the water filtration system was the need for the sand to settle in the biosand filter whenever the filter was moved. However, the students neglected this state when determining the venue of the live demo. The students decided to move the water purification system the day of the live demo, which disrupted the sand-filter and resulted in a device that didn't function properly. Yet another instance where students neglected to utilize their system model was during the first prototype build phase. The students didn't consider ease of manufacture. Several key components such as the sand filter were located in regions that prevented easy access even though the students noted that the sand would have to be replaced when the biolayer becomes too thick such that it prevents adequate water flow.

Overall thoughts regarding incorporating systems engineering in undergraduate education

Several students struggled to find value utilizing systems engineering which could possibly be due to the maturity level of students. In addition without doing the entire systems engineering approach, it was difficult to see how one model affects the outcome. Students also typically thought that tinkering would be faster than developing the entire design on paper first. In the students' defense, they generally don't have much manufacturing experience, thus they aren't capable of determining how feasible a design will be until they go to try and build it first. In addition, it is difficult for them to realize all the types of interactions including developing logical architectures until they physically have the device in front of them. The models that the students found most useful were the logical architectures and stakeholders/feature attributes. Almost the entire class was familiar with stakeholders due to a previous design class, while physical architectures they have been exposed to them in their daily life, thus it seemed more trivial to them and not as important. Everyday we see physical architectures without being aware of the design's logical architecture.

In order to convey to students the validity of systems engineering, we would change the course such that the students are "re-engineering a product" that is a more specific, tangible product rather than starting from scratch. One of the major strengths of systems engineering is it allows people to understand key elements of a current product in order to find opportunities for future improvements. Thus, the development of the systems models should be an iterative process especially as more information is learned about stakeholder needs. To stress this fact, next time we would force students to revise their models after the initial build of the cardboard mockup with the goal of producing an even better product at the program's end.

In conclusion, some components of systems engineering can be taught to undergraduate engineering and science students not enrolled in systems engineering with the main challenge of "buying-in" to the validity of creating these models.

Acknowledgment

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