AC 2011-1370: ALL INNOVATION IS INNOVATION OF SYSTEMS: AN INTEGRATED 3-D MODEL OF INNOVATION COMPETENCIES

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All Innovation Is Innovation of Systems: An Integrated 3-D Model of Innovation Competencies

Abstract

The development of the future generations of innovators is of central interest to engineering educators. What are the competencies of innovation and how do we develop them? There is a considerable body of scholarly, business, and popular literature concerned with the characteristics of innovative people and organizations, in which attention is frequently focused on individual creativity and other personality traits, organizational cultures, and other non-technical capabilities. We argue here that the typical descriptions of innovation competencies are correct but incomplete, lacking critical dimensions that are essential for planning an educational curriculum and assessing progress within it.

The foundation of our model of innovation competencies rests on our definition of innovation: The ability to develop novel solutions to problems that result in significantly enhanced stakeholder satisfaction. As engineering educators, we believe that innovation is only effective when it includes the full cycle leading to delivery of improved stakeholder outcomes, and this introduces challenges beyond an initial creative mental leap. We accept that (1) certain discipline-specific technical competencies traditionally addressed by engineering educational programs can be important to innovation, and (2) we likewise accept that a collection of non-technical traits are also vital to successful innovators. However, in this paper we argue that the combination of (1) discipline-specific technical skills and (2) non-technical competencies is missing an entire dimension. This third dimension is a technical one, but not specific to a discipline: it is the set of systems competencies. The resulting three-dimensional model provides an integrated view of the competencies of innovation, against which educators can plan, educate, and measure accomplishment.

By separating but coupling the three dimensions of this model, we have a tool spanning different engineering programs, providing an integrating framework for conversation across our specialties. We have identified assessment indicators used in demonstrating the attainment of these competencies. A novel aspect of these demonstrations along the systems dimension is their explicit use of Model-Based Systems Engineering (MBSE) artifacts. The emergence of MBSE methods has a transformative impact on not only performance of systemic aspects of engineering, but also education in these methods. MBSE transforms “bag of tricks” and “body of knowledge” engineering requiring decades to learn into scientifically-based systemic skills that can be learned and explicitly demonstrated by undergraduates.

This paper is based upon work carried out by a summer institute on innovation, building on historical work on institutional learning outcomes, industrial systems engineering methodology, and global research in characteristics of innovators. As a part of our institution’s emphasis on

innovation, we are now piloting the related methods in specific disciplines, two of which are illustrated in the paper.

Introduction

Innovation has become an increasingly important concept to corporate, academic, and public organizations[1,2,3,4,5,6,7,8] and as a measure of national competitiveness [9,10,11]. In a survey of companies and business executives[11], it is reported that 72% of them rank innovation as a 'top three' strategic priority. Therefore it has become essential to Engineering Educational programs to ensure that their graduates enter the workforce with skills that will allow them to be effective innovators and to be able to function well in innovative organizations. We have two main goals for this document. The first is to help define the set of program level competencies that are essential for a student to be prepared to enter the modern innovative environment. The second goal is to provide some tools to help illustrate ways in which innovation education can be implemented by giving examples of in-class activities that can help students develop innovation skills, and by defining a set of program-level objectives to help programs assess innovation education within their curricula.

While our discussion and our examples largely center on instilling innovation skills in Engineering majors, any technical undergraduate program, including Engineering, Mathematics, and the Sciences, should be able to provide the appropriate skills within their curricula.

While it is clear that successful innovative teams need to have strong innovation competencies as a group, we feel that it is also important for an individual working on an innovation team to have a working knowledge of all of these competencies as well. It is in this light that we feel it is up to educational programs to ensure that all students develop competence in these areas.

A definition of innovation

An examination of the literature shows that there are many different definitions of innovation[12]. Most of these definitions center on aspects of innovative thought, including creative problem solving and creating an environment that fosters innovation. It is important to note that technical educational programs not only should instill the ability to creatively solve problems (which we would call invention), but also the ability take these novel ideas and incorporate them into real-world solutions that result in an improvement over the status quo, as experienced by stakeholders. Based on this reasoning, for the purposes of this document, <u>innovation is defined as the ability to develop novel solutions to problems that result in significantly enhanced stakeholder satisfaction.</u>

The innovation competency space

Innovation is clearly a trans-disciplinary endeavor. To function in an innovative environment, it is essential that modern technical professionals have depth of knowledge in a technical discipline. This knowledge, although required, is not sufficient for effective innovation to occur. Discipline-specific knowledge must be accompanied by a set of competencies that allow for creative, team-based problem solving (which we will call Discovery Competencies, a term coined by Dyer, Gregersen, and Christensen[6]), as well as discipline-independent systems-based product development competencies (Systems Competencies). Furthermore, teaching these skills independently is not enough to produce innovators. Students must be taught how to use these skills simultaneously and purposefully to produce innovative design solution. We propose that the convergence of these three skill sets creates an "innovation competency space" comprised by the three axes shown in Figure 1.

While many of the individual competencies that we mention are already components of technical programs, one key component of our approach is that students must be ready to purposefully synthesize solutions within the Innovation Competency Space. It is with this in mind that we present two example activities that help focus students' efforts towards working in these intersections.

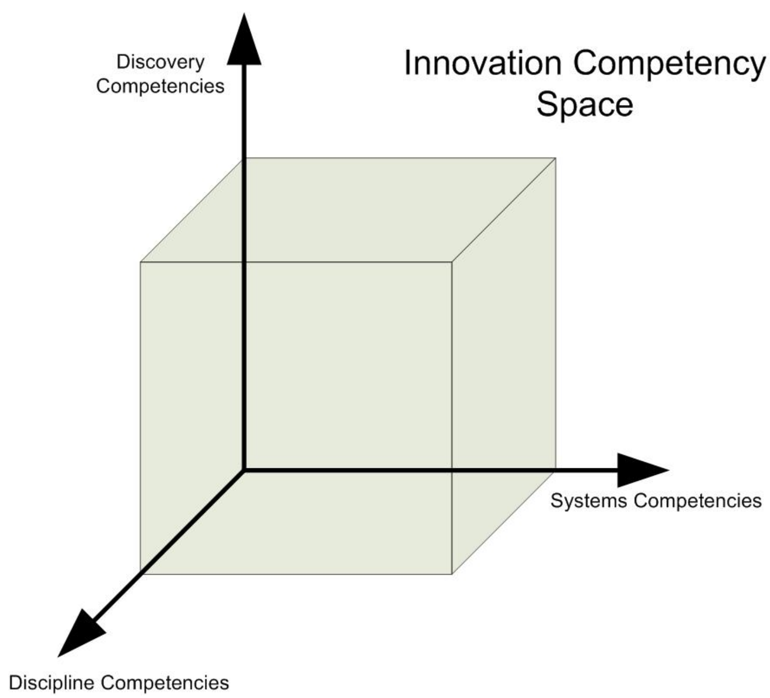

Figure 1: The Innovation Competency Space

Discovery Competencies

There is a considerable body of scholarly, business, and popular literature concerned with the characteristics of innovative people and organizations, in which attention is frequently focused on individual creativity and other personality traits, organizational cultures, and other non-technical capabilities. In reviewing, comparing, and considering these various views on the nature of innovativeness, we came to the conclusion that the study and practice of innovation is somewhat challenged by a lack of common terms of reference. Often, various authors have applied slightly different labels to fundamentally the same concepts, or have subdivided and categorized the same ideas in slightly different ways. For purposes of our discussion and to explain and illustrate one axis of the three dimensional conceptual model of innovation, we have chosen "The Innovator's DNA," as presented by Dyer, Gregersen, and Christensen[6].

The competencies defined by the Innovator's DNA, the authors refer to as, "Discovery Skills" [6]. The term, "skill," refers to task proficiency. While specific task proficiency is certainly an essential element of Engineering education for effective innovation, we envision the boundaries of the innovation space as broader than task specific skills alone. We refer to the axes of the innovation space as competencies because they encompass skills, traits, behaviors, and knowledge. Discovery Competencies form the axis of the three dimensional innovation space that facilitates bringing the other two axes into the practice of innovation. The Discovery Competencies provide context and points of reference for the analysis and synthesis focused skills within the Systems Competencies, which draw on the Discipline Competencies in their manifestation. In their work, Dyer, Gregersen, and Christensen portray their five, "discovery skills", using a DNA metaphor, "Associating is like the backbone structure of DNA's double helix; four patterns of action (questioning, observing, experimenting, and networking) wind around this backbone, helping to cultivate new insights". [6]

Associating, or the ability to draw previously unidentified connections between seemingly disparate entities, is the core of the Discovery Competencies. Associating is at the foundation of the first half of our definition of innovation in this paper, "the ability to develop novel solutions to problems that result in significantly enhanced stakeholder satisfaction." Associating in the Discovery Competency context supports and informs the synthesis functions in the Systems Competencies, and is informed by the Discipline Competencies and their corresponding domain knowledge.

Questioning the status quo and challenging conventional wisdom is an excellent way of discovering areas for pursuing innovation. Questioning in the Discovery Competencies context informs and supports the analytical functions within Systems Competencies, and is informed by a solid foundation in Discipline Competencies and domain knowledge. An innovator well grounded in Discipline Competencies and domain knowledge can often avoid wasting effort on questions that have already been answered in the discipline.

Observing is the Discovery Competency which informs all others. All of the other Discovery Competencies, Systems Competencies, and Discipline Competencies, require input; this input comes from observation. Specific to the Discovery Competencies that form one axis of the three dimensional innovation space, observation seeks out possibilities for the elements of our definition of innovation. Observation seeks problems and/or potential problems. Observation seeks solutions and/or potential solutions. Observation seeks stakeholders and/or potential stakeholders, and those factors that lead to their satisfaction. Observation supports and informs the analysis focused Systems Competencies, and is informed by Discipline Competencies and domain knowledge. The Discipline Competencies and knowledge already provided by a quality Engineering education provide the innovator with what to observe and how to observe it.

Experimenting to many may draw images more closely associated with Discipline Competencies. Useful, effective innovative experimentation is always well informed by Discipline Competencies and domain knowledge, but innovative experimentation is not limited to the laboratory. Particularly in the three dimensional conception of innovation which we propose, in an Engineering education context, innovative experimentation draws heavily on the informative power of modeling in the Systems Competencies. Innovative experimentation seeks to test the various elements of innovation: the problem, the solution, the stakeholders, and their satisfaction. Discipline Competencies and domain knowledge enable experimenting with competency in how to experiment. Systems Competencies both enable experimenting through the application of modeling techniques, and are informed and supported in both their analysis and synthesis functions by innovative experimentation.

Networking is the Discovery Competency that puts the human element in the Discovery Competencies. Innovation as a practice happens between people. While similar in many respects to more traditional social or professional networking, innovative networking's purpose is to enable the other Discovery Competencies. An innovative network affords the innovator with opportunities for questioning, observing, experimenting, and most importantly, associating. Like the other Discovery Competencies, networking supports the components of innovation: the problem, the solution, the stakeholders, and stakeholder satisfaction. Networking is informed and supported by Discipline Competencies and domain knowledge in that they enable an informed and meaningful discussion, ideally with both other technical experts in the same field, and those whose specializations are in other fields. Systems Competencies provide structure and an executable method to innovation networking.

The Discovery Competencies, taken as a whole, form one axis of the three dimensional space in which innovation occurs. Though somewhat outside the scope of traditional Engineering or other technical undergraduate education, the Discovery Competencies constitute a set of teachable skills, traits, behaviors, and knowledge which can be displayed, demonstrated, evaluated, and mastered. When employed in concert with the Discipline Competencies and domain knowledge of traditional Engineering and technical education, and the model based Systems Competencies commonly associated with systems engineering, the innovators' Discovery Competencies of associating, questioning, observing, experimenting, and networking effectively posture new Engineering, Mathematics, and Science graduates for success in the contemporary innovation environment. Appendix A provides a potential assessment platform for the Discovery competencies, including Learning Outcomes and Rubrics.

The use of model-based methods in engineering of systems has become prominent in recent years. However, based on the literature on innovation, we believe that the structured integration of the systems competencies as a key dimension of the Innovation Competencies, and the use of model-based methods to demonstrate those competencies, constitutes a novel combination that transforms what was otherwise a landscape of intangible traits into a teachable and demonstrable set of undergraduate skills.

Systems competencies

The competencies summarized along this axis are technical in nature, and may be taught and learned as technical subject matter closely aligned with education in science, engineering, and mathematics. However, these <u>Systems Competencies</u> are not specific to any <u>single</u> discipline such as Mechanical, Electrical, Chemical Engineering or similar studies—instead, these competencies appear in all of them, and connect them, as seen in Systems Engineering. (For purposes of this paper, "discipline" refers to the technology-specific major study areas such as those just listed; we realize that systems engineering can also be considered a discipline, although the term is not used that way here.)

Students show competencies of this systemic type through their ability to explicitly address the following skills, knowledge, and capabilities. Each of these is discussed at length in Appendix B, including specific competency criteria for each competency:

1. Describing the target of innovation from a **<u>systems perspective</u>**;
2. Applying a **<u>system stakeholder view</u>** of value, trade-offs, and optimization;
3. Understanding system's **<u>interactions and states</u>** (modes);
4. Specifying system **<u>technical requirements</u>**;
5. Creating and analyzing **<u>high level design</u>**;
6. Assessing solution **<u>feasibility, consistency, and completeness</u>**;
7. Performing system **<u>failure mode and risk analysis</u>**;
8. Planning system **<u>families, platforms, and product lines</u>**;
9. Understanding **<u>roles and interdependencies across the innovation process</u>**.

This paper further describes how the above system competencies are addressed using Model-Based Systems Engineering (MBSE). This approach means that the engineered system and its environment are described by explicit system "models" [16,17,18,19,20,21,22,23]. Models are explicit relational data structures, frequently graphic or tabular, sometimes mathematical; Figures B3-B15 of Appendix B provide examples. In addition to advantages the MBSE approach offers to the engineering process itself [13,14,15], we are concerned here with the educational advantages it offers to the student and teacher:

A. MBSE models, even though they are relatively abstract, provide a more concrete way to learn and practice many systems-related competencies that otherwise have a reputation of requiring decades of professional experience to internalize.

B. Use of MBSE models also means that there is a more direct, consistent, and objective means for the student to demonstrate competency, and for the educator to evaluate it.

C. There are deep connections between the Systems Competencies axis and the other two axes of Figures 1 and 2. The MBSE approach makes it much clearer how these axes are connected at a detailed level:

    a. The MBSE approach makes it much clearer how ideas of the Discipline Competencies axis, learned in major courses, are connected to the Systems Competencies axis.

    b. The MBSE approach makes it much clearer when <u>synthesis</u> competencies appear within the overall competency set (as distinguished from analysis competencies also appearing, for example). These are then much more clearly connectable to the Discovery Competencies axis.

By providing a "map" through Innovation Competency Space, this approach makes it easier for the student and professor to travel up and down levels of abstraction, connect ideas from different areas, to recognize the innovation process as it occurs in or across specific disciplines, and to improve overall ability to understand and practice innovation.

Explaining Systemic Aspects of Disciplines

As shown in Figure 2, the System Competencies provide a common means for explaining a number of ideas that appear in specific discipline programs, but are in fact not specific to disciplines. For example, system "logical roles" might be identified as needed to provide heat exchange, distribution of forces, and radiation of electromagnetic energy. These systemic roles may be identified and manipulated before and independent of their allocation to specific physical design components or technologies. The overall set of systems concepts are summarized by the information model of Figure B2, Appendix B. Its systemic concepts of states, physical interactions, logical roles, interfaces, and other systemic ideas can be mapped into each discipline.

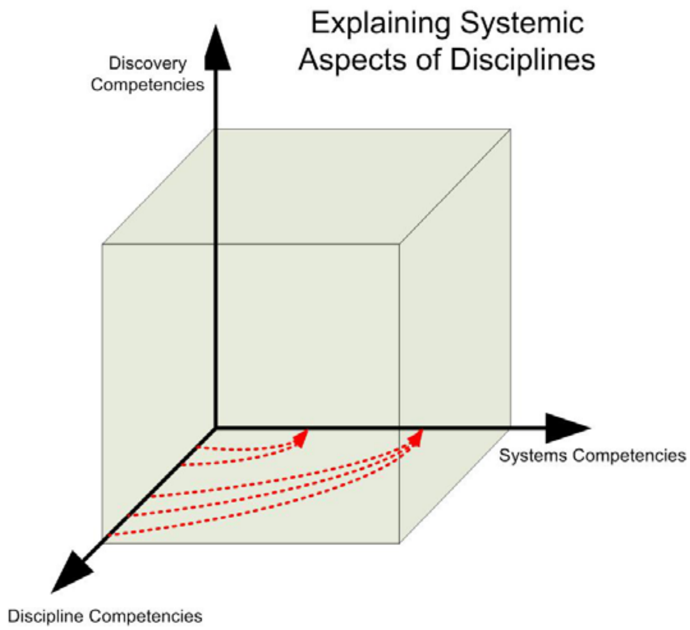

Figure 2: Explaining Systemic Aspects of Disciplines

Identifying Points of Synthesis, Empowered by Discovery Competencies

The system axis identifies four kinds of information that must be synthesized during any innovation (whether consciously or unconsciously), distinguishing those points of synthesis from a number of other analysis aspects that also apply to innovations (see competencies S3, S4, S5, and S8 in Appendix B for discussion of these synthesis points). Although it is well known that synthesis and analysis call for different competencies, we believe that the specific areas in which synthesis is demanded are not always well-identified, so the "spotlights" shined by this perspective are of value.

Furthermore, we connect the competencies of the third axis (the Discovery Competencies) to these four points of synthesis along the systems axis. This is because the competencies of synthesis call upon the much broader range of discovery competencies—in fact, we see that third axis as providing exactly the empowering competencies that are needed at the four points of synthesis identified by the systems axis (Figure 3).

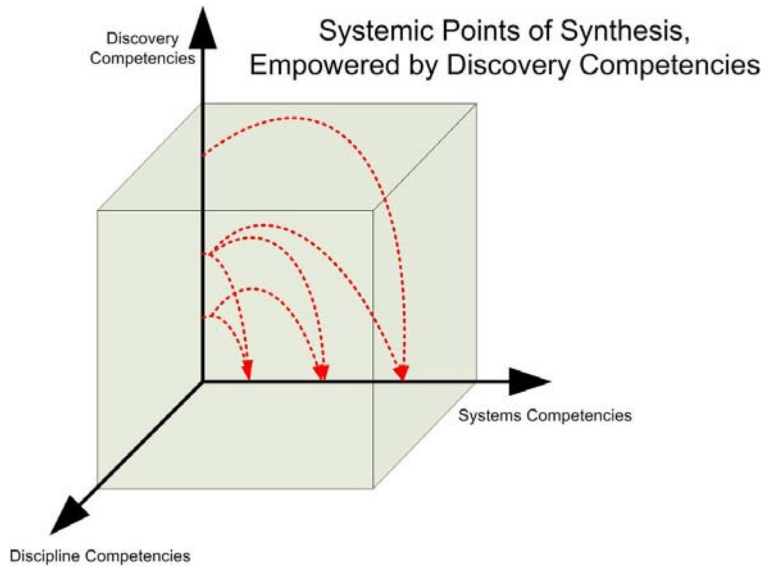

Figure 3: Systemic Points of Synthesis, Empowered by Discovery Competencies

Discipline Competencies

Technical programs have many ways in which they optimize the discipline-specific competency of their students. Contributions to this area come from faculty expertise, internal assessment programs and constraints introduced by accreditation boards. Since this is an area of emphasis, and that disciplines vary broadly in appropriate technical competencies, we will leave it up to individual programs to determine appropriate discipline centered competencies.

Examples from education of future innovators

Example 1: Combining Systems, Discipline and Discovery Competencies in Civil Engineering Senior Design.

One of the System Competencies is applying a system stakeholder view of value, trade-offs, and optimization. This skill has been a focus in the senior design course in civil engineering at Rose-Hulman for about eight years. The importance of this skill to effective innovation is realized every year.

In the senior design course, student teams use a decision matrix to evaluate options for the most important design decision of their project. The students identify and research options. To develop the list of options, they rely on the discovery competencies: associating, questioning, observing, experimenting, and networking. To determine which options are viable, they use their Discipline Competencies. Only the viable options are evaluated in the decision matrix. Their client either picks or approves the criteria the students use to evaluate the options, and the client decides the relative importance of each criterion. Table 1 shows an example decision matrix.

Criterion	Weight	Option A	Option B	Option C
Initial Cost	25%	2	1	3
Annual Maintenance Cost	25%	3	2	3
Public Opinion	20%	1	3	2
Adaptability for Future Uses	15%	3	3	2
Aesthetics	10%	3	2	3
Recyclability	5%	1	1	3
Weighted Average Rating		2.3	2.1	***2.7***

Table 1. Example of a decision matrix used to evaluate three design options. If a higher rating is better, Option 3 is the best option for the client chosen criteria and relative weights.

As faculty, we encourage the students to explore innovative options in addition to the traditional options for this important design decision. For example, the traditional structural materials for buildings and bridges are concrete, steel, masonry, and timber. Over the last few years, our students have also explored recycled plastics, structural insulated panels (SIPs), insulating concrete forms (ICFs), and autoclaved aerated concrete. It would be easy for students to let the excitement of a novel solution to the problem drive them to choose the innovation, even if it is not the best choice for that problem for that client.

The decision matrix helps ensure that the students recommend the best option based on the client's goals embodied in the criteria. Examples of criteria over the years include initial cost, maintenance cost, recyclability, CO_2 emissions generated, and aesthetics. Sometimes the traditional solution has been the best choice, and sometimes the innovative solution has proven to be the best. For example, in one building project from 2009 students found that traditional wood framing was the best structural material for that situation for that client's goals. However, on a different building project for a different client in 2010, students found that structural insulated panels (SIPs) were the best structural material. In both cases, during initial meetings the clients expressed interest in innovative solutions. In 2009, though, the best solution was not innovative. Without applying a system stakeholder view of value, trade-offs, and optimization (Systems Competencies), the students might have recommended an innovative solution (result of the Discovery Competencies) that would not have maximized the client's satisfaction. That is not effective innovation.

Example 2: Introducing Systems Skills in a Biomedical Engineering Physiology Course

The goal of this assignment was to introduce students to "systems thinking." It was designed for a Junior level Physiological Systems course, and was given as an in-class 1 hour assignment.

<u>High Level Design of a Prosthetic from a Physiological Perspective: The artificial heart</u>

Part A: Defining external interactions of the natural physiological system/ identifying system requirements

Step A1: Treating the cardiac system (i.e. the heart) as a black box, list all external elements with which the heart must interact.

Example elements: Aorta, Sympathetic NS

Step A2: For each of the external elements listed in step 1, write a sentence or two describing how the elements interact, focusing on key parameters that must be controlled for effective interactions. Collectively, these elements will give us a set of requirements for our system.

Example interactions:

- *The fluid output of the heart must be sent into the aorta at a pressure of between 80 and 150 mmHg and at a range of flow rates from 4-25 l/min.*
- *The heart should respond to activity of the sympathetic nervous system by increasing its output up to a maximum of 5X the normal output.*

Part B: Developing a logic architecture model of the proposed prosthetic

Step B1: Develop a list of subsystems that must be incorporated into the design of a prosthetic to meet the constraints defined in part A. What we are looking for here is a "logical architecture model" rather than a "physical architecture model". Therefore your subsystems should be in terms of function only, and NOT in terms of technical design subsystems. When appropriate, assign multiple constraints to a single subsystem.

Example Subsystems:

- *Vessel Coupling Subsystem*
- *Sympathetic Activity Measurement Subsystem*

Step B2: Combine your subsystems into a block diagram for the system.

Step B3: Place a box around your block diagram. Outside of this box, show connections to external elements identified in Step A1.

Figure 4: Systems Thinking Assignment

While the students did not have sufficient time to fully develop their designs (in the future using a 3 hour lab period might be a better choice), the assignment forced students to think about device development and physiological systems in a different way. All student groups did develop a logic architecture model and attempted to make connections to external system requirements. In addition, students were introduced to key systems-based vocabulary, including the terms *Systems Requirements* and *Logic Architecture Model* which have specific technical definitions and were novel concepts to most of the students.

The goal of this assignment was to introduce the students to “systems thinking” concepts, primarily to understand the importance on taking interactions into account when designing a system (see Outcome S1 in Appendix 2). Furthermore, this assignment introduced the concept of a high-level logic-architecture model, in which students think about functional interactions when developing an initial design instead of thinking about the physical pieces that they will use.

In terms of the Innovation Competency Space, this requires the student to use all three competency axes. Part A of the assignment, in which students are asked to identify Systems Requirements, requires students to think about discipline specific concepts (in this case cardiac physiology) in a new way. Part A also introduces students to key concepts of Systems Competencies. Part B of the assignment provides an opportunity for students to utilize Discovery Competencies to develop novel logic architecture models for the system.

Conclusions and implications

The three dimensional model of innovation competencies has tremendous potential. Several authors have attempted to define innovation and/or innovativeness in a variety of contexts. The volume of material that continues to be generated in scholarly, professional, and popular outlets is indicative of the emphasis the topics are receiving. Engineers, scientists, and other technical experts have long been at the forefront of technological and entrepreneurial innovation. In the contemporary innovation environment, a “quality,” Engineering, scientific, or technical undergraduate education, by definition, must be one that prepares the graduate to function effectively in that environment.

Viewing innovation in three dimensions, bounded by three mutually supporting and reinforcing axes is important because the lack of effective application along any one axis leads to less than effective innovation practice. As can be seen in the learning outcomes included in the appendices, the three dimensional innovation model aids the development of Engineering, science, and technical curricula. Much of what is implied by the three dimensional view of innovation for Engineering, science, and technical undergraduate education is already happening in many institutions. The educational process in Engineering, science, and technology could be made even more powerful by a more purposeful application of these ideas.

We strongly encourage colleagues from all fields to join us in pursuing a more innately innovative population of future Engineers, Scientist, and Technologists through an integrative approach to discipline-founded, systems-enabled, and discovery-informed undergraduate educational practice. The three dimensional model of innovation has broad applicability, including to the refinement of Engineering, science, and technology education practice itself. Bearing in mind that purposeful innovation is most effective when supported on all three axes, and that innovation happens in the space created between all three, we look forward the future of Engineering, science, and technology education, in the innovation space.

As we continue to pursue the goal of better preparing Engineering, science, and technology graduates to function effectively in the contemporary innovation environment, we envision general concentrations of short-term, mid-term and long-term goals. The short-term goal is to continue to gather examples of Engineering, science, and technical education practice that fulfill an integrative approach to teaching innovation competencies. The mid-term goal is to develop new methods of Engineering, science, and technical education practice that develop student competencies along all three dimensions of the innovation space. The long term goal is to achieve an imbedded "innovation across the curricula," which seamlessly integrates aspects of the three dimensions of innovation into the total undergraduate experience. We invite colleagues with an interest in furthering any of the above goals to contact us.

Appendix A: Discovery Competencies: Proposed Learning Outcomes and Rubrics

Discovery Competency D1: Connect seemingly unrelated questions, problems or ideas from different fields into a single, coherent question, problem or idea.

Primary Traits: A passing submission for this criterion must:

1. Describe the contributing questions, problems or ideas, which must come from at least two different fields (e.g., electrical engineering, biology, economics, music).
2. Describe a connection between the contributing questions, problems or ideas that is not clearly anticipated.

Potential Artifacts: persuasive essay, blog, journal, presentation

Additional Information:

1. To be coherent, the connection between the contributing questions, problems or ideas must be elucidated. For example, "Fiber optic strands are relatively small, inexpensive and not chemically reactive. Monitoring cracking in concrete structures is difficult because the members are often not exposed and the cracks must be relatively deep before they are visible to the naked eye. Embedding fiber optic strands in the concrete will not affect the performance of the concrete, but if a crack passes the fiber, the fiber will break. The loss of signal along the fiber is an indication of the depth of crack propagation."

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Discovery Competency D2: Develop questions that challenge the status quo.

Primary Traits: A passing submission for this criterion must:

1. Describe the situation or current mode of operation (status quo) and perceived constraints.
2. Present one or more questions that challenge the status quo.
3. Explain how each question is a challenge to the status quo.

Potential Artifacts: reflective essay, blog, journal, presentation

Additional Information:

1. Common approaches to this type of questioning include asking "Why?", "Why not?", and "What if?" For example, "Why is program accreditation done every *six* years?"
2. It can be helpful to imagine an opposing situation or viewpoint. For example, "What if program accreditation was done by employers rather than agencies?"

3. It can be helpful to consider new constraints that prohibit the status quo or to consider the removal of constraints. For example, "What if faculty could not be involved in the program accreditation process?"

Discovery Competency D3: Use observations of human behavior to develop new ways of doing things.

Primary Traits: A passing submission for this criterion must:

1. Describe the current or traditional way of performing a certain task.
2. Describe the proposed new way of performing the task.
3. Describe the observation that led to the proposed new way, the group that was observed, and how the new way is related to the observation.

Potential Artifacts: persuasive essay, blog, journal, presentation

Additional Information:

1. Observations may be made of customers, clients, co-workers, suppliers, companies, etc.
2. For example, "Students check their text messages more frequently than their email, so faculty could send course emails as text messages to the class."

Discovery Competency D4: Develop new insights by provoking unexpected responses in an experiment or series of experiments.

Primary Traits: A passing submission for this criterion must:

1. Describe the experiment(s): what/who is the subject of the experiment(s), what variable is being modified, what is the anticipated response.
2. Describe the observed response and explain why it was unexpected.
3. Formulate a hypothesis as to why the observed response might have occurred.

Potential Artifacts: lab report, essay, presentation

Additional Information:

1. Experiments need not be laboratory based. Experiments can include testing human behavior. For example, "If all the chairs were removed from the dining hall, how would students respond at lunch?"
2. Experiments involving living subjects must be pre-approved by the instructor.

Discovery Competency D5: Learn something from outside their background.

Primary Traits: A passing submission for this criterion must:

1. Identify the relevant part of the student's background (e.g., field of study, ethnicity, gender) and from where the new knowledge came.
2. Describe the new knowledge.

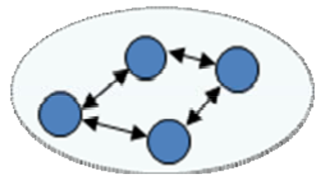
Potential Artifacts: persuasive essay, blog, journal, presentation

Additional Information:

1. The new knowledge does not need to come from a book, journal or webpage. It can come from interaction with someone from a different occupation, culture, generation, etc.

Appendix B: Systems Innovation Competencies

All innovation is innovation of systems. "Systems" are collections of interacting components (man-made, natural, human, frequently of mixed technologies or disciplines), in which the interactions lead to emergent (desirable or undesirable) *properties of the system as a whole*:



Systems Engineering is concerned with the life cycle engineering of those systemic properties, providing an *integrating technical coordination across individual engineering disciplines*[13,14,15]. The arrival of Model-Based Systems Engineering (MBSE) marks the transition of systems engineering from a prose-based, intuitive, craft or body of knowledge into a science-based engineering discipline, joining the other science-based engineering disciplines. This enables the *earlier learning* of specific "hard" technical systems engineering competencies that cut across individual program disciplines, and likewise cut across the "softer" competencies also vital to innovation:

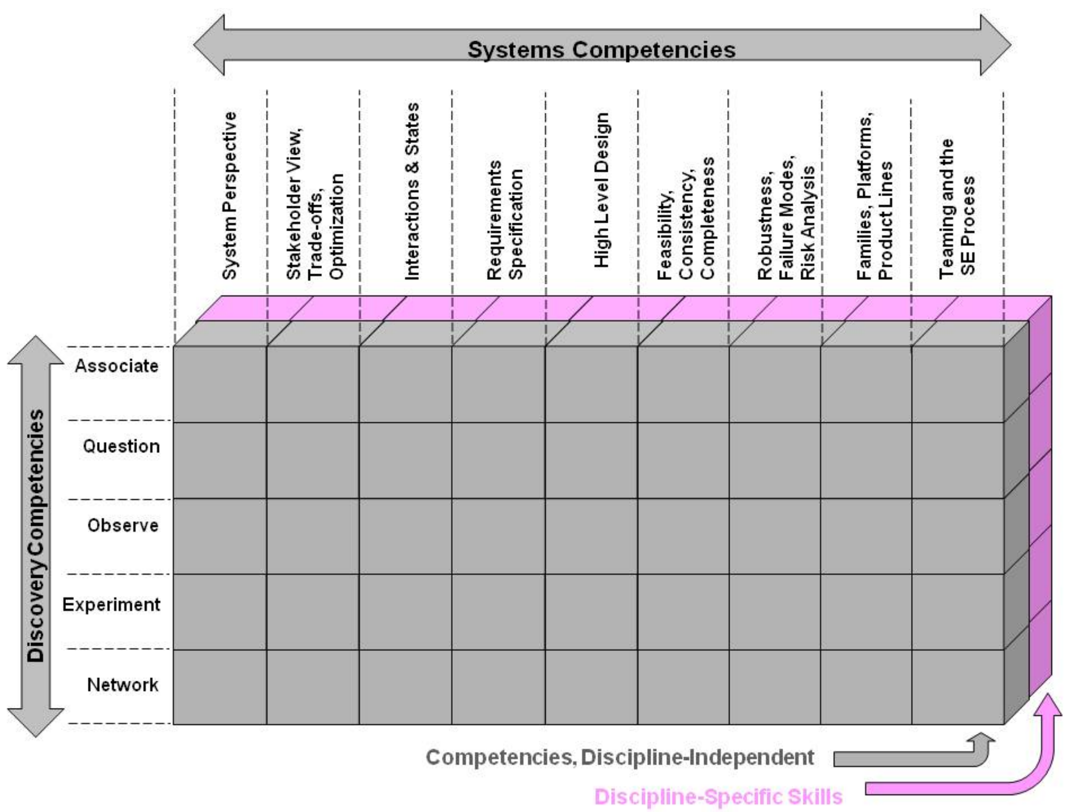


Figure B1: Identifying Points On Two of the Three Innovation Competencies Axes

The Systems Information Model

The MBSE approach to systems changes the way we think about the representation of systems, causing us to focus more explicitly on a set of systemic ideas and a set of information data structures that represent them in graphic, tabular, or other "views" of the resulting integrated "system model". Figure B2 summarizes main aspects of the information model framework used, described further in references listed [16,17,18,19,20,21,22,23]. The use of these concepts is fundamental to the learning outcomes and related model-based artifacts used to demonstrate the system competencies in the balance of Appendix B.

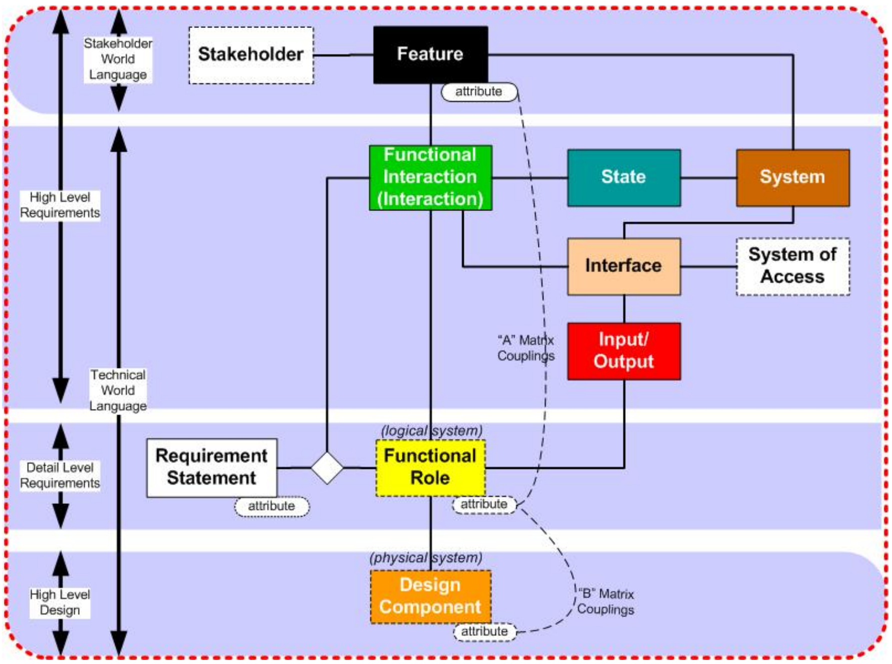


Figure B2: The Systems Information Model Framework

The Systemic Competencies: Proposed Learning Outcomes and Rubrics

In practice, the innovator or innovation team simultaneously applies (1) discipline-specific competencies, (2) discipline-independent <u>systems</u> competencies, and (3) Discovery competencies. (Refer to the Figure B1.)

The following sections describe type (2): the discipline-independent systems skills (competencies) for each of the "columns" of the Figure B1, referring to the column headings of that diagram.

In both education and practice, the situation surrounding these systemic competencies has changed. The recent emergence of Model-Based Systems Engineering (MBSE) methods has transformed what was previously an implicit, intuitive set of skills, acquired over decades of practice, into a more explicit, model-based framework of thought, communication, and action. This means that significant acquisition and practice of these skills can occur during undergraduate education. This is an important acceleration over the decades of practice that had been claimed as required prior to the arrival of model-based methods.

Accordingly, for each Systems Competency, the following sections describe:

- Primary Traits: The general systems-oriented competency to be demonstrated, stated without reference to models or model-based methods.
- Potential Artifacts: Specific model-based artifacts that the student can use to learn, practice, and demonstrate the general competency in concrete form. Examples are provided.

Additional supporting information resources can be found in the references.

Systems Competency S1. Apply a Systems Perspective to innovation of a modeled system.

Primary traits: A passing submission for this criterion must:

1. Demonstrate awareness and understanding that a contemplated new or modified entity is in turn a component of a larger system of users, output consumers, upstream or downstream entities, external infrastructure, materials, operators and maintainers, or other environment with which it interacts, having emergent overall systemic impacts on the larger system as a whole.
2. Demonstrate awareness and understanding that a contemplated new or modified entity is itself made up of multiple interacting components, leading to emergent overall impacts.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include: Domain Model, Interface Definitions, Logical Architecture Model. (See Figures B3, B4 examples.)

Additional information:

1. The systems perspective is inherently holistic, and evidence of holistic thinking is expected by this criterion.
2. This criterion includes strong awareness of the existence and identity of the entities external to and interacting with the innovated entity.

Systems Competency S2. Discover, understand, validate, and apply a system stakeholder view essential to modeled system competitive value, trade-offs, and optimization.

Primary traits: A passing submission for this criterion must:

1. Demonstrate awareness of the existence and identity of each of the major stakeholders or stakeholder groups that are impacted by the contemplated innovation.
2. Demonstrate analysis of and sensitivity to the values (both positive and negative) and characteristics of each stakeholder type, and the relative weighting of those relationships as they bear on the summary statement of the goals and values of the innovation, as well as trade-offs in considering alternative approaches.
3. Demonstrate analysis and consideration of the weighted stakeholder impacts and values in analyzing trade-offs and optimizing solutions to the goals of the innovation.
4. Demonstrate that the fit of competitive alternatives to the contemplated innovation have been included in analysis and competitive evaluation.
5. Demonstrate that knowledge of these stakeholder views has been validated with the appropriate representatives of the stakeholder groups.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include: Stakeholder Informal System Needs Statements, Models of Stakeholder Features, Feature Attributes, Stakeholders, and Stakeholder Advocates. (See Figures B5, B6 examples.)
Additional information:

1. Awareness of and sensitivity to stakeholder perspectives is not an entirely hard technical trait, but in part a soft or humanistic sensitivity. It is "getting inside" the mindset, thought patterns, behaviors, tendencies, traits, culture, or other characteristics of the stakeholder groups.
2. There is a key difference between system stakeholders (those with a stake in the outcome of the innovation) and external actors (the entities with which the system directly interacts). Not all stakeholders are actors, because some stakeholders are not direct actors, but are reached only indirectly (example: shareholders). Not all actors are stakeholders, either. However, some actors can be stakeholders and some stakeholders can be actors.

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Systems Competency S3. Synthesize, analyze, and validate modeled system interactions and states (modes).

Primary traits: A passing submission for this criterion must:

1. Demonstrate that concepts of innovated system modes, including those of delivery, operation, maintenance and support, and retirement or disposal have been synthesized, analyzed, evaluated, and validated with stakeholders.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include: System State Model, associated System Interactions, and system Operational Scenarios validated by system stakeholders. (See Figure B7 for example State Model, with Interactions.)

Additional information:

1. This criterion includes strong awareness of the nature, behavior, and characteristics of the entities external to and interacting with the innovated entity.
2. This criterion includes synthesis as well as analysis and evaluation of the synthesized result.

Systems Competency S4. Synthesize, analyze, evaluate, and validate modeled technical system requirements in an innovative context.

Primary traits: A passing submission for this criterion must:

1. Demonstrate the synthesis, analysis, evaluation and validation of statements of system technical requirements, sufficient for use to drive design and development of plans for system verification.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include: Detailed Interaction Models and associated functional Requirements Statements, including key attributes. (See Figure B8 for example Interaction Diagram, with related Requirement Statements and Requirement Attributes.)

Additional information:

1. The requirements prose should be explicitly consistent with the rest of the associated interaction model, so that the requirements are effectively input-output characterization of the subject system.

Systems Competency S5. Synthesize, analyze, evaluate, and optimize modeled system logical and physical architecture and functional allocations to system high level design.

Primary traits: A passing submission for this criterion must:

1. Demonstrate synthesis of one or more decompositions of system overall behaviors into partitioned behavior subsets, typically interacting with each other.
2. Demonstrate synthesis of one or more physical architectures, and allocations of decomposed functional roles onto the physical architectural components, representing a candidate solution(s).

3. Demonstrate analysis and evaluation of the candidate solution(s), optimization of solution parameters, and selection of one or more optimum solutions.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include (but are not limited to): Logical architecture model, decomposition of functional requirements and their allocation to logical subsystems, physical architecture model, allocation of logical roles to components of physical architecture, comparison of alternative architectures and attribute values, scored in stakeholder feature space, trade-offs and design rationale. (See Figure 10 example allocation of logical roles to physical architecture, with allocated requirements, Figure 11 example alternate physical architectures, and Figure 12 example attribute coupling models.)

Additional information:

1. This criterion includes synthesis as well as analysis and evaluation of the synthesized result.
2. The scope of the systems engineering portion of this criterion is about high level (architectural) design, frequently spanning multiple technologies, and not necessarily the detail design specific to a single discipline or technology. However, the high level and detail designs should be in alignment.

Systems Competency S6. Verify the feasibility, consistency, and completeness of system requirements and the design of solution(s).

Primary traits: A passing submission for this criterion must:

1. Demonstrate the analysis of feasibility, consistency, and completeness, using paper analysis, design review meetings, simulations, prototypes, and/or various types of system tests.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include (but are not limited to): Consistency and completeness tracing analysis of Needs, Features, Requirements, and Design. Also, design review meeting minutes, system simulations, prototypes evaluations, pilot system evaluations, product alpha and beta test results. (See Figure 13 for example tracing of consistency of Stakeholder Need, Feature, Requirements, Decomposition, and Capability.)

Additional information:

1. This criterion includes analysis and evaluation.

Systems Competency S7. Discover, analyze, and plan for system failure modes and their associated risks, leading to robust system design.

Primary traits: A passing submission for this criterion must:

1. Demonstrate awareness of the physical failure modes that can occur on the part of system design components and external environment—both man-made and natural.
2. Demonstrate understanding of the nature, severity, and probability of impacts of these failure modes on the stakeholders of the system.
3. Demonstrate synthesis of control strategies, alternate designs, mitigations, or other approaches to address those failures whose nature, severity, and probability justify attention.

Potential artifacts: Artifacts appropriate to this criterion include: Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis, Control Strategy. (See Figure 14 example model-based FMEA.)

Additional information:

1. This criterion involves analysis and evaluation of failure modes and their effects.
2. It also involves synthesis of responses, and analysis and evaluation of their sufficiency.

Systems Competency S8. Synthesize, analyze, and optimize configured product lines or system families across market segments, applications, or customers, from a common system platform.

Primary traits: A passing submission for this criterion must:

1. Demonstrate awareness of the existence of differing market segments, applications, or customer sets for the innovated system, along with their distinguishing and common characteristics.
2. Demonstrate synthesis of alternate configurations of the innovated system, appropriate to the different segments or applications, aligned and optimized to their characteristics.

Potential artifacts: *Model-oriented* artifacts appropriate to this criterion include: Configurable Platform Model, Configured Family Instances. (See Figure 15 example product line model.)

Additional information:

1. This criterion involves synthesis, as well as analysis and evaluation of the synthesized results.

Systems Competency S9. Understand and coordinate the systemic technical inter-dependencies of roles across the systems innovation process, allocated across a team.

Primary traits: A passing submission for this criterion must:

1. Demonstrate understanding of the different systems innovation process roles that must be fulfilled, including their different characteristics and inter-dependencies, and the risks associated with performance.
2. Demonstrate synthesis of an allocation of these responsibilities to real organizational assets (people, facilities, suppliers, partners), including an awareness of risks specific to this allocation.
3. Demonstrate awareness of performance as it occurs, and action to address risks as they arise, leading to success.

Potential artifacts: Artifacts appropriate to this criterion include: Systems Engineering Management Plan (SEMP), minutes of SE process reviews.

Additional information:

1. This criterion involves understanding, as well as synthesis of organizational solutions, and analysis and evaluation of those solutions and their performance.

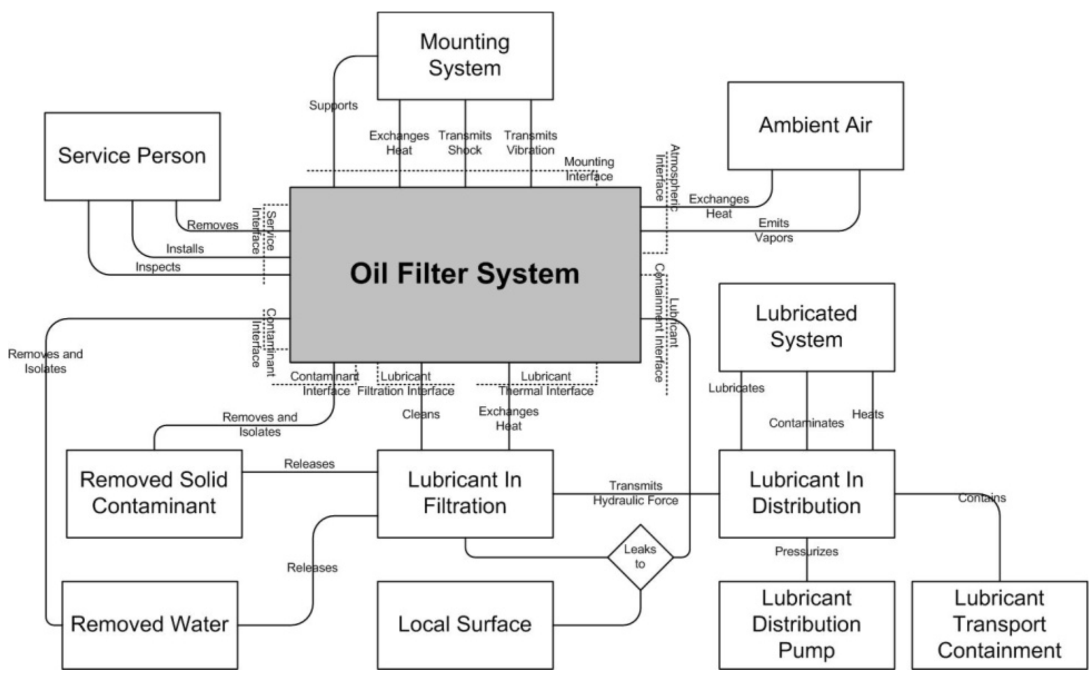


Figure B3: Example Domain Model

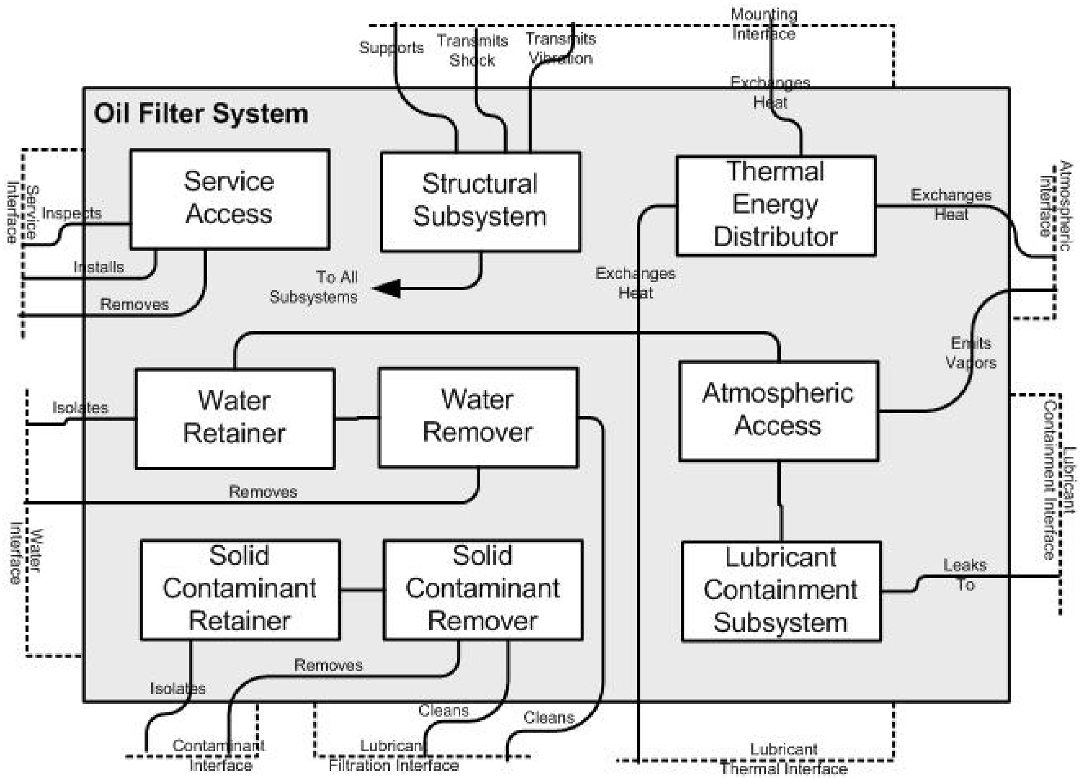


Figure B4: Example Logical Architecture Model

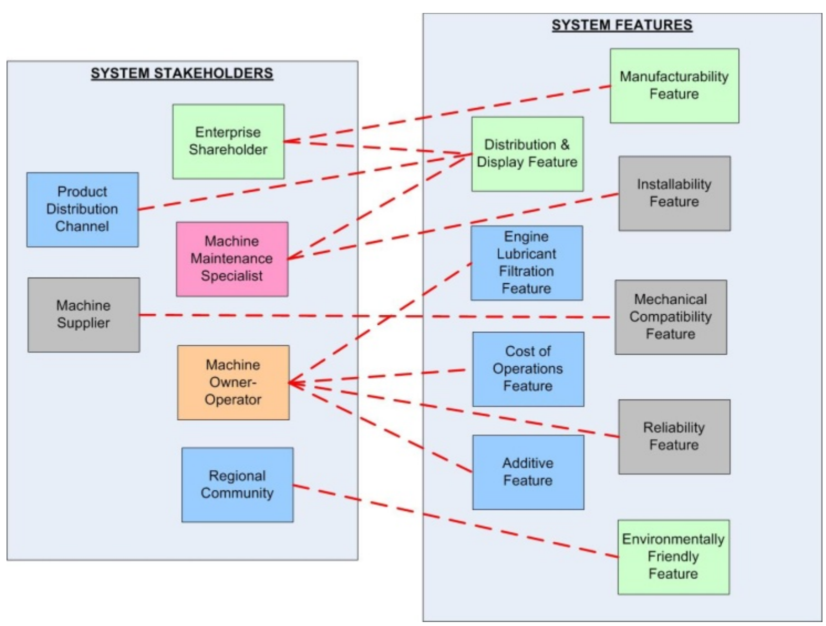
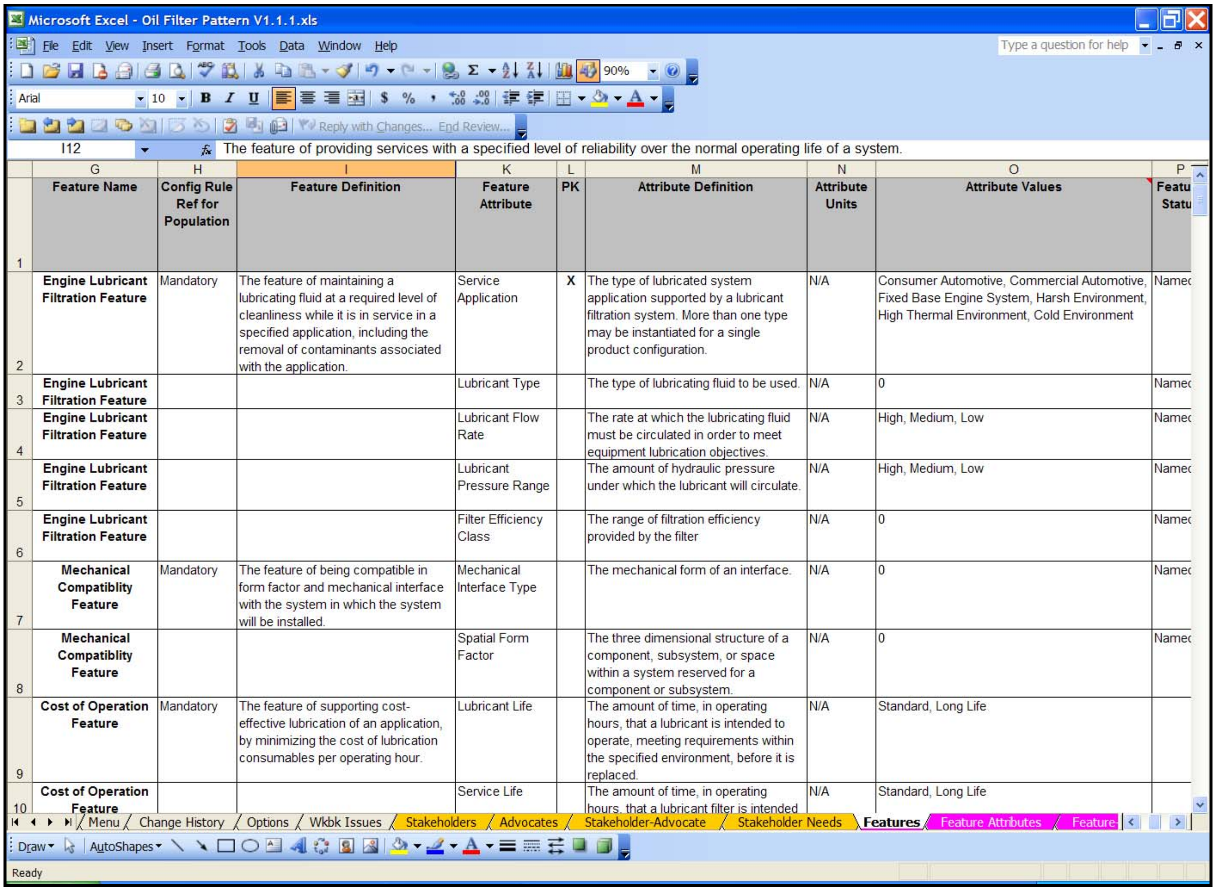


Figure B5: Example Stakeholder-Feature Model Tracing



	Feature Name	Config Rule Ref for Population	Feature Definition	Feature Attribute	PK	Attribute Definition	Attribute Units	Attribute Values	Featu Statu
2	**Engine Lubricant Filtration Feature**	Mandatory	The feature of maintaining a lubricating fluid at a required level of cleanliness while it is in service in a specified application, including the removal of contaminants associated with the application.	Service Application	X	The type of lubricated system application supported by a lubricant filtration system. More than one type may be instantiated for a single product configuration.	N/A	Consumer Automotive, Commercial Automotive, Fixed Base Engine System, Harsh Environment, High Thermal Environment, Cold Environment	Namec
3	**Engine Lubricant Filtration Feature**			Lubricant Type		The type of lubricating fluid to be used.	N/A	0	Namec
4	**Engine Lubricant Filtration Feature**			Lubricant Flow Rate		The rate at which the lubricating fluid must be circulated in order to meet equipment lubrication objectives.	N/A	High, Medium, Low	Namec
5	**Engine Lubricant Filtration Feature**			Lubricant Pressure Range		The amount of hydraulic pressure under which the lubricant will circulate.	N/A	High, Medium, Low	Namec
6	**Engine Lubricant Filtration Feature**			Filter Efficiency Class		The range of filtration efficiency provided by the filter	N/A	0	Namec
7	**Mechanical Compatiblity Feature**	Mandatory	The feature of being compatible in form factor and mechanical interface with the system in which the system will be installed.	Mechanical Interface Type		The mechanical form of an interface.	N/A	0	Namec
8	**Mechanical Compatiblity Feature**			Spatial Form Factor		The three dimensional structure of a component, subsystem, or space within a system reserved for a component or subsystem.	N/A	0	Namec
9	**Cost of Operation Feature**	Mandatory	The feature of supporting cost-effective lubrication of an application, by minimizing the cost of lubrication consumables per operating hour.	Lubricant Life		The amount of time, in operating hours, that a lubricant is intended to operate, meeting requirements within the specified environment, before it is replaced.	N/A	Standard, Long Life	
10	**Cost of Operation Feature**			Service Life		The amount of time, in operating hours, that a lubricant filter is intended	N/A	Standard, Long Life	

Figure B6: Example Feature Attributes

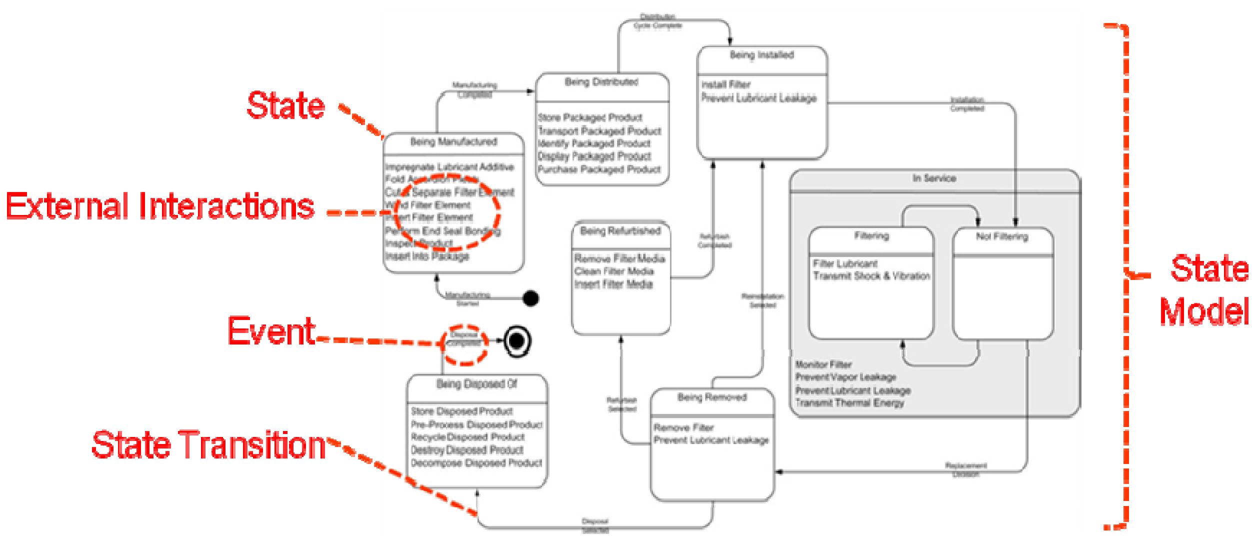
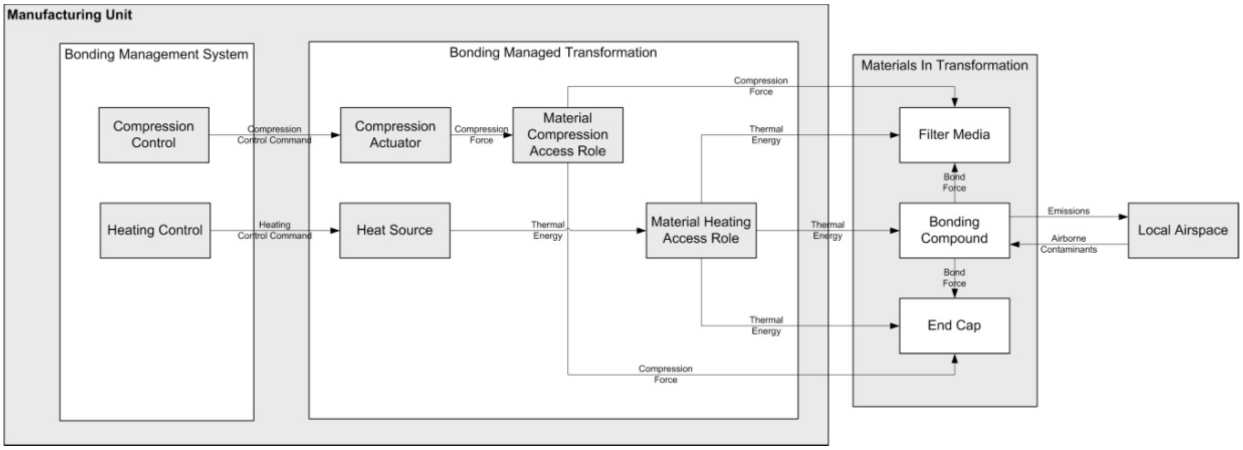


Figure B7: Example State Model, showing external Interactions



Oil Filter Manufacturing System Requirements (for filter media sealing):

- Requirement OFM-32: "The Manufacturing System shall deliver a Compression Force of [Min Bond Force] for a period of [Min Bond Time]".

- Requirement OFM-33: "The Manufacturing System shall deliver Thermal Energy sufficient to maintain a bond temperature of [Min Bond Temperature] for a period of [Min Bond Time]."

Oil Filter Product Requirements:

- Requirement OF-51: "The Oil Filter shall operate at lubricant pressure of [Max Lubricant Pressure] with structural failure rates less than [Max Structural Failure Rate] over an in-service life of [Min Service Life]."

Figure B8: Example Interaction Diagram, with Requirements Statements

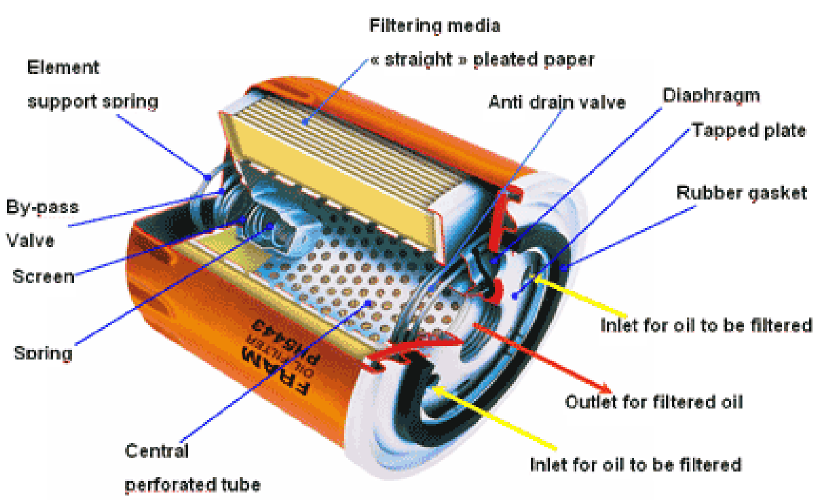
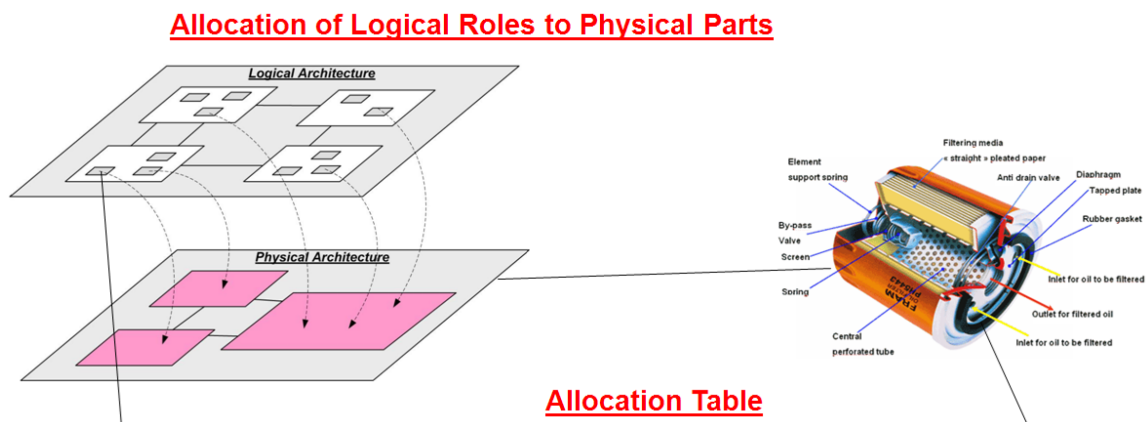


Figure B9: Example Physical Architecture Diagram



Interaction	Logical Role	Requirement		Physical Component
Filter Lubricant	Solid Contaminant Remover	The system shall remove solid contaminants from the lubricant flow, creating a pressure drop not to exceed [Max Pressure Drop] , meeting the particulate removal profile of [Particulate Removal Profile]., during a component in-service life of at least [Min Service Life].		Filter Media
Filter Lubricant	Structural Subsystem	The system shall maintain seal integrity over an in-service period of at least [Min Service Life].		Filter Seal

Figure B10: Example Allocation of Logical Roles to Physical Components, Including Allocated Requirements

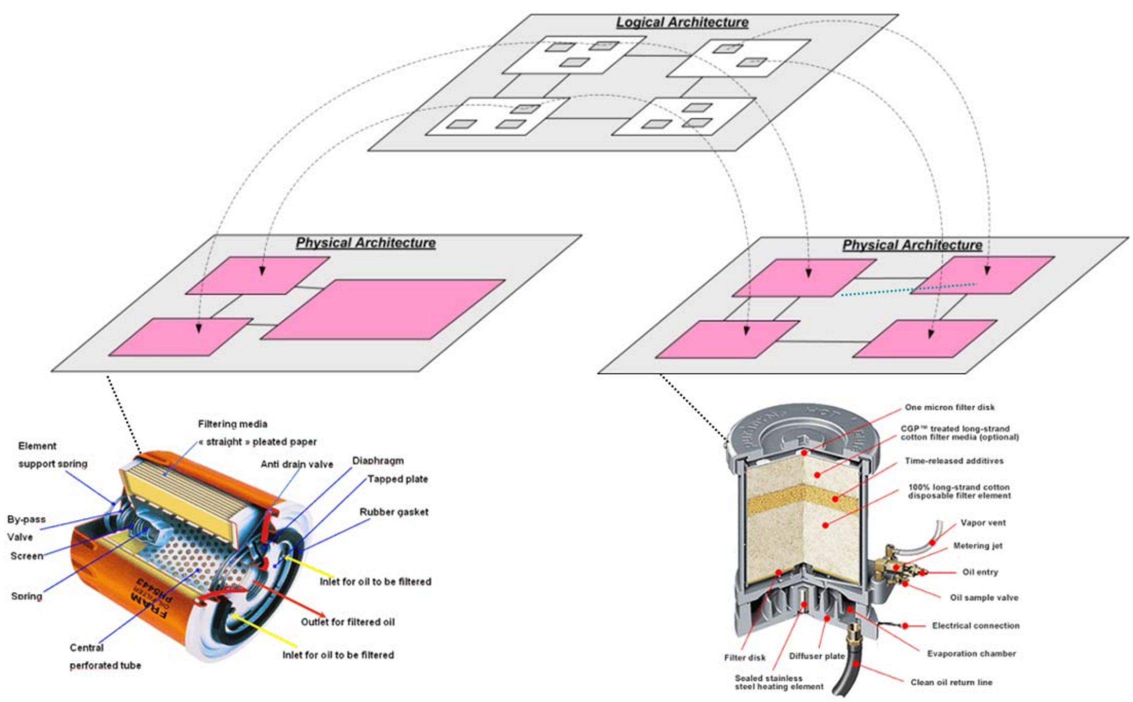


Figure B11: Example Alternate Physical Architectures and Allocations

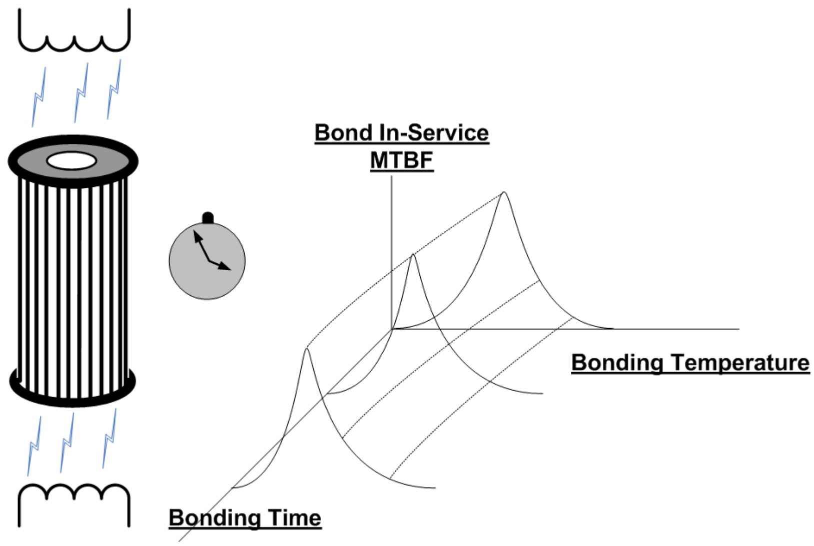


Figure B12: Example Attribute Coupling: Manufacturing to Product

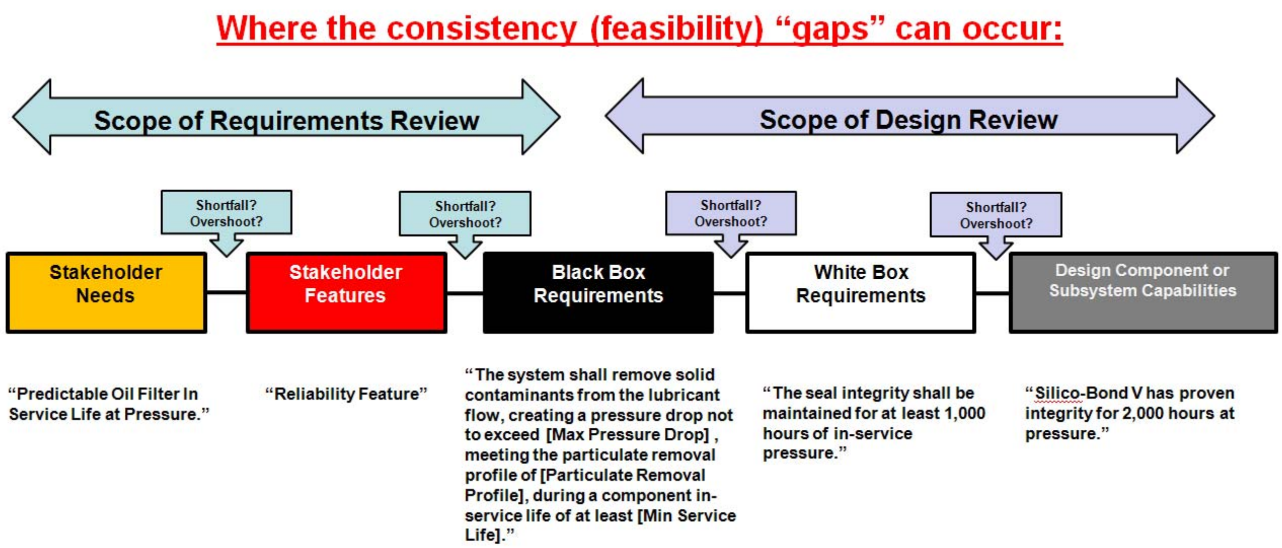


Figure B13: Example Tracing of Needs, Features, Requirements, Decomposition, and Component Capabilities

Feature	Failure Impact (=FMEA Effect)	Impact Severity Score	Counter Requirement	Failure Mode	FM Probability
Engine Lubricant Filtration Feature	Lubricant Contamination	4	System does not remove solid contaminants from lubricant flow.	Filter Media Rupture	0.005
Engine Lubricant Filtration Feature	Lubricant Pressure Loss	5	System exceeds pressure drop limit through filter	Filter Media Clogging	0.012
Reliability Feature	Filter Leaks Oil	3	System does not maintain seal integrity over in-service period.	Filter Bond Rupture	0.002

Figure B14: Example Model-Based Failure Modes & Effects Analysis (FMEA)

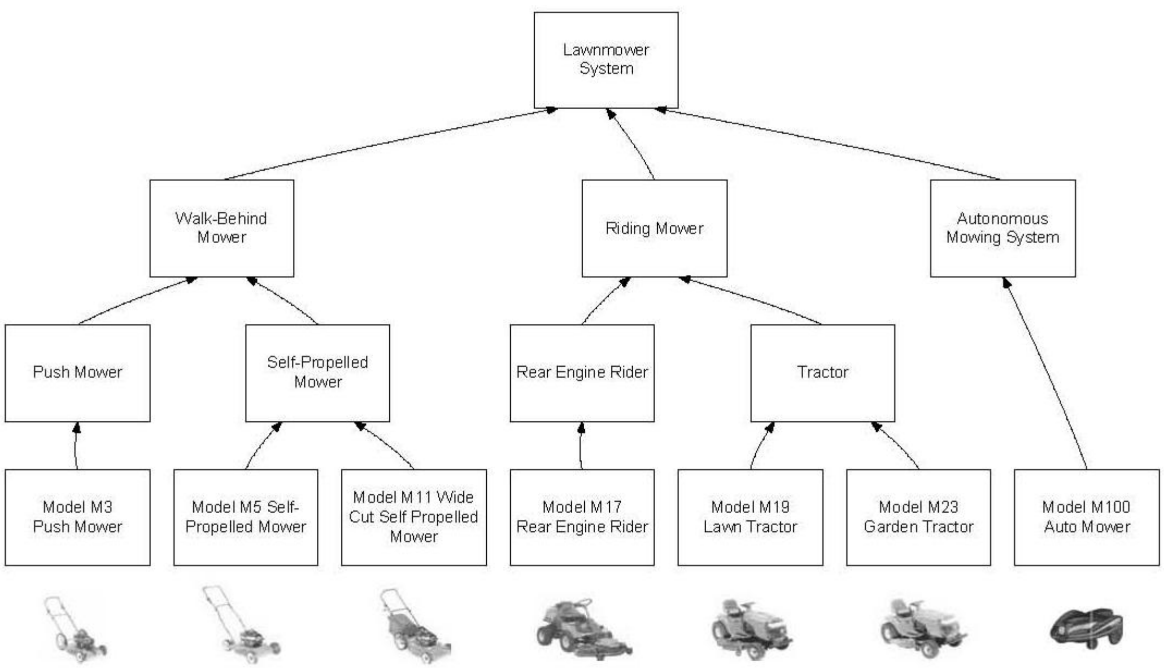


Figure B15: Example Product Line Family Model

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