Systems Engineering Educational Strategies: Incorporating Active Learning with a Healthcare Case Study

Dr. Sandy L. Furterer, University of Datyon

Dr. Sandy Furterer is an Associate Professor at the University of Dayton, in the Department of Engineering Management, Systems and Technology. She recently came from industry as a VP of Process Transformation for Park National Bank in Columbus, Ohio.

Dr. Furterer received her Ph.D. in Industrial Engineering with a specialization in Quality Engineering from the University of Central Florida in 2004. She received an MBA from Xavier University, and a Bachelor and Master of Science in Industrial and Systems Engineering from The Ohio State University.

Dr. Furterer has over 25 years of experience in business process and quality improvements. She is an ASQ Certified Six Sigma Black Belt, a Certified Quality Engineer, an ASQ fellow, and a certified Master Black Belt. Dr. Furterer is an author or co-author of 4 reference textbooks on Lean Six Sigma, Design for Six Sigma and Lean Systems, including her latest book: Lean Six Sigma Case Studies in the Healthcare Enterprise by Springer publishing in 2014.

Dr. Furterer is an author or co-author of 7 refereed journal articles, and 23 refereed conference proceedings publications on process modeling, lean six sigma, process improvement and engineering education. She has 76 conference presentations on operational excellence, process improvement, lean six sigma, business process architecture, engineering education.

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Sandra L. Furterer, Ph.D., MBA
Associate Professor of Engineering Management, Systems, and Technology
University of Dayton
Email: sfurterer1@udayton.edu
University of Dayton
300 College Park,
Dayton, OH 45469
Phone: (937) 229-2475

Abstract

Over the last nearly 100 years, Systems Engineering principles, methods and tools evolved from several engineering related disciplines. The university's Department of Engineering Management, Systems, and Technology, teaches their Management of Engineering Systems course, modeled on the Systems Engineering Body of Knowledge (SEBoK). This body of knowledge is wiki based, making it easy to navigate. The SEBok is designed to provide an overview of the material, with multiple references for accessing additional content and depth of material. However, the SEBoK is not designed for Masters students, who have little to no background in the SEBoK to easily learn or apply the material. The author has incorporated multiple educational strategies into a Systems Engineering course including: 1) information-providing lectures, 2) inquiry-oriented case studies, 3) active or performance-based active learning exercises, 4) cooperative team-based system design, 5) creativity-inducing methods based application of systems engineering tools. Central to several of the strategies was to adapt a healthcare case study from the author's prior process and systems improvement work experience, to guide the students to better understand, synthesize and apply systems engineering. The case study supports the inquiry-oriented, active learning and case study pedagogies, helping students to learn by seeing examples of the application of the materials to real-world problems. In this paper, we will describe some of the tools and activities that were used to design a women's healthcare center for providing healthcare services in a one-stop, spa-like environment. The case study was used to help students learn and apply systems engineering tools and methods.

Keywords: Systems Engineering, Case studies, healthcare

Introduction:

Over the last nearly 100 years, Systems Engineering principles, methods and tools evolved from several engineering related disciplines. The concepts, methods and tools of Systems Engineering are becoming more important due to many internal and external factors affecting organizations. Some of these factors include: increasing regulatory environments, increasing technology and interfaces, global economies, socio-political structures, the climate and environment, need for organizational communication, capturing every-changing needs of customers, and overall complexity, to name just a few.

Three organizations have developed the Systems Engineering Body of Knowledge (SEBoK), namely, the International Council on Systems Engineering (INCOSE), the Institute of Electrical and Electronic Engineers Computer Society (IEEE-CS), and the Systems Engineering Research Center (SERC). The first version was published in 2010. This body of knowledge represents "… a widely accepted, community-based and regularly updated baseline of systems engineering (SE) knowledge" (SEBok). The university's Department of Engineering Management, Systems, and Technology, in the School of Engineering teaches their Management of Engineering Systems, modeled on this SEBoK. This body of knowledge is wiki based, making it easy to navigate. The online SEBok is designed to provide an overview of the material, and includes multiple references for accessing additional content and depth of material. The SEBoK does not meet the needs of engineering management masters students, who have little to no background in the SEBoK, to easily learn and apply the material. Like many bodies of knowledge, the material provides a cursory understanding of the material, assuming that the reader has an extensive prior knowledge and experience within the knowledge base. A key learning objective of the course is to be able to synthesize and apply the systems engineering methods and tools to a real-world system design project. To achieve this goal, the author has adapted a healthcare case study from the author's prior process and systems improvement work experience, to guide the students to better understand, synthesize and apply systems engineering. The case study is aligned to the Vee Life Cycle model, and teaches principles and tools in each of the following phases: Concept of Operations; Requirements and Architecture; Detailed Design; Implementation, Integration, Test and Verification; System Verification and Validation; Operation and Maintenance. The case study supports the active learning and case study pedagogies, helping students to learn by seeing examples of the application of the materials to real-world problems.

Teaching Methods and Case Study Pedagogy:

Teaching methods are techniques that help motivate students to do what they need to do to learn course material. Gentile (2016) categorized teaching methods into the following types: 1) information-providing, 2) inquiry-oriented, 3) active or performance-based, 4) cooperative, 5) mastery-based and 6) creativity-inducing. Each method will be briefly discussed. 1) Information–providing type of learning typically uses lecture and demonstrations to convey information (Gentile, 2016). 2) Inquiry-oriented methods of learning encourage the student to examine and search the information to discover the truth. It includes using case studies to encourage the higher level learning (Gentile, 2016). 3) Active or performance-based methods encourage the students to be actively involved with and participate in their learning. Active learning is designed to have the student practice the application of the material while they are coached and provided feedback from the instructor (Gentile, 2016). 4) Cooperative methods are active learning techniques designed to teach collaborative skills (Gentile, 2016). 5) Mastery-based methods are focused on providing a minimum mastery of the information. Finally, 6) creativity-inducing methods include brainstorming and other techniques that encourage the student to think differently to come up with different and creative ideas (Gentile, 2016). All of these methods are probably best applied when used with several or all of the methods together to enhance learning.

Case studies are descriptions of real-world examples that can be used in the classroom to help the students apply the principles, methods and tools of the course material (Carroll and Rosson, 2006)

Developing and using case studies to enhance higher level learning in engineering education is part of the active learning pedagogy (Yin, 2009). Active learning engages students in higher order thinking assignments (Bonwell & Eison, 1991). The case study can help integrate practice with theory (Swart, 2009, 2010) (Hunt, 2012). Case studies promote critical thinking (Popil, 2011). They have the potential to reveal rich contextual findings of a personal, social, and pedagogical nature, that cannot easily be obtained by other methods (Miller, 1997).

Methodology and Educational Learning Strategies:

This section describes the educational learning strategies applied in a graduate-level engineering management systems engineering course that included the following methods: 1) information-providing lectures, 2) inquiry-oriented case studies, 3) active or performance-based active learning exercises, 4) cooperative team-based system design, 5) creativity-inducing methods based application of systems engineering tools.

1) Information-providing lectures:

Traditional lecture PowerPoint presentations were developed for the course material, and provided to the students prior to the classroom presentations. The lecture time was kept to a minimum, and interspersed with the case study and active learning exercises.

2) Inquiry-oriented case studies:

The healthcare case study was used to provide a real-world example of how the systems engineering principles, methodology and tools could be applied. Additional detail and examples of the case study, as well as an assessment of the case study's effectiveness are provided in the Case Study section.

3) Active or performance-based active learning exercises:

The instructor integrated active learning exercises into each classroom session within the prepared lecture materials. The students worked together in teams on the exercises, that enabled the use and practice of the systems engineering principles and tools. Examples of active learning exercises follow.

Active Learning Exercise Example 1: What is a System?

Principle being applied: Definition of a system and types of systems.

Exercise A: What is a system, in your own words…

Exercise B: Service and Service Systems

- A service system is one that provides outcomes for a user without necessarily delivering hardware or software products to the service supplier.
- Discussion: Provide examples of a service system

4) Cooperative team-based system design:

The culminating assignment that was worth 30% of the course grade included a team-based system design project. The students were able to select a system to design, where they had to apply the systems engineering principles, methods and tools framework, shown in Figure 2. Both the case study and the system design project followed this framework. The System Design and Research Project included the design of a system, and application of the methods, tools and principles learned in the course. The students could design any type of product or service system that would show the use of the tools identified in the instructor's System Engineering Methodology, Activities & Tools Framework. They were to create the concept, requirements, architecture and design, and also develop sample integration, test, verification and validation, operation and maintenance sample deliverables. The students were to first research the literature for their chosen system, to understand the design concepts, to make their system design as realistic as possible. The design should be grounded by the available research and case studies. The students should reference any materials that they used within their report, using a consistent citation format. If they leveraged other resources, such as subject matter experts, they were also to provide a reference and acknowledgement of their expertise and help.

5) Creativity-inducing methods based application of systems engineering tools.

Many of the systems engineering tools encouraged and enabled creativity inherent in the tool. Examples of tools that helped the students generate creative solutions were: Pugh Concept Selection Technique (Pugh, 1991), Quality Function Deployment (Akao, 1990); process scenarios (TOGAF, 2011); business/customer and systems requirements analysis; and the process architecture map developed in part by the author. The Pugh Concept Selection technique is a simple tool that allows the students to generate alternative system design concepts, and then compare and select the best design based upon the multiple decision criteria. It uses brainstorming to generate the alternative design concepts. Quality Function Deployment (QFD) is a tool that is used to ensure that the customers' desired requirements are met through the proposed technical or system requirements. Process scenarios are used to brainstorm possible ways that the system will be used, and the processes associated with them. This tool is an excellent creativity tool to design the best processes to meet the customers' and systems requirements. The process architecture map combines the traditional process map with an information architecture. This helps to extract the information and knowledge that will be used with the future state processes for the system that is designed.

Vee Phase	Activities	Tools	Principles
Phase 1: Concept of Operations	• Define strategic goals • Define goals of mission (mission analysis) • Perform stakeholder analysis • Perform conceptual selection	Strategic goals: • Value gap analysis; External analysis; Internal analysis; SWOT analysis Mission analysis • Project charter with risk analysis • SIPOC • Stakeholder analysis • Pugh Concept Selection Technique	• Complexity • Emergence (whole > sum of parts) • System of system • Hierarchy • Boundary
Phase 2: Requirements & Architecture	• Develop Logical Architecture • Develop Business requirements • Develop system requirements	Logical Architecture: • Value Chain & Functional Decomposition • Class Diagram Requirements: • Business requirements • Process Scenarios • System requirements • Use Case Diagram	• System dynamics (behavior, system elements) • Cybernetics (information flow) • Systems thinking • Abstraction • Views
Phase 3: Detailed Design	• Perform detailed design • Perform systems analysis	Detailed Design: • Use cases • Process Architecture map • Physical Architecture Model (Hierarchy) • Physical Block Diagram; SysML Block Definition Diagram; SysML Internal Block Diagram • QFD • Simulation Systems Analysis: • Selection criteria	• Systems analysis • Wholeness and interactions

		• Trade off analysis; Effectiveness analysis; Cost analysis; technical risk analysis • Justification report	
Phase 4: Integration, Test & Verification	• Perform system implementation • Perform system integration • Perform system validation • Perform system verification	• Integration constraints • Implementation strategy • System elements supplied • Initial operator training • Verification criteria • Verification test cases and results • N-squared diagram	• System elements • Modularity • Interactions • Networks • Relationships • Behavior
Phase 5: System Verification and Validation	• Perform system verification • Perform system validation	• Verification and Validation criteria • Verification and Validation test cases and results	• Synthesis
Phase 6: Operation & Maintenance	• Perform training • Perform certification • Perform risk assessment and planning for maintenance • Perform disposal and retirement activities	• Training plan and materials • Certification plan and materials • Operations Manuals • Performance reports • Maintenance and service plans; FMEA • Disposal and retirement plan	• Control behavior and feedback • Encapsulation (hide internal workings of system) • Stability and Change

Figure 1: Systems Engineering Methodology, Activities & Tools Framework

Case Study:

The case study was an integral learning strategy applied within the systems engineering course. It enabled the inquiry-oriented method, the active learning exercises, the cooperative team-based system design, and creativity-inducing methods. We will describe the case study in more detail with examples of the application of some of the tools. We will then provide an assessment of its effectiveness in helping the students learn, synthesize, and apply the materials.

Case Study Overview:

A healthcare case study was used as a guiding example of how to apply the systems engineering methodology and tools taught in the course. The students then had a semester-long project where they designed their own system by applying the same method and tools. The case study described how the systems engineering methods and tools were used to design a women's healthcare facility and the processes performed to provide the women's services. Many outpatient facilities are focusing on providing comprehensive services to women in a comfortable setting. In a qualitative study of women who had received a mammogram in the prior three years, without a history of cancer, satisfaction was related to the entire experience, not just the actual mammogram procedure. The authors of the described study found seven satisfaction themes from the focus groups: (1) appointment scheduling, (2) facility, (3) general exam, (4) embarrassment, (5) exam discomfort/pain, (6) treatment by the technologist, and (7) reporting results (Engelman, Cizik and Ellerbeck, 2005). This supports the focus of designing a seamless experience for women in the Women's Center through applying the systems engineering methodology, tools, and principles.

The systems engineering Vee system design methodology was used to organize the case study, and help the students learn the methodology (SEBok). The following phases included:

The principles and tools applied in each phase are shown in Figure 1 - Systems Engineering Methodology, Activities & Tools Framework. This was developed by the author based on the Vee model phases.

The complete case study consisted of the application of the systems engineering design activities, tools and principles taught in the course. The students were expected to use the systems engineering framework to design their own system. The case study report was quite extensive and consisted of 69, single spaced pages, with figures of the tools. The instructor also provided a detailed PowerPoint presentation that she presented to the class across multiple sessions.

Select active learning exercises within the first four phases of the Vee Model will be discussed next.

Concept of Operations Phase 1:

The Concept of Operations Phase is the first phase in the Systems Engineering Vee Life Cycle Model (SEBoK). The purpose of the phase is to perform an analysis of the mission and define its strategic goals.

One of the tools is to perform a value gap analysis of the proposed internal functions that a system could provide, to identify the system's mission. The healthcare value gap analysis is shown in figure 2. This helped the students understand how to apply this tool.

Criteria: Functions	Current State	Future or Desired State	Gap
Schedule service	Excellent care, but long delays in getting an appointment	Excellent care, appointments in 3 days or less	Long delays in getting an appointment
Register Patient	Long delays in registration	Only wait 10 minutes for registration	Long delays in registration
Perform Service	Excellent care, but long delays for service	Excellent care, less than ½ delays	Long delays waiting for service
Provide Imaging results	Average 57 hours for results	Same day results	Average of 33 hours
Provide spiritual care	Spiritual care not available on site	Spiritual care on site	Lack of spiritual care resources
Connect to Cancer Center	No process or technology, process silos	Process & technology for seamless connectivity	Lack of process and technology to connect to cancer center
Perform Surgery	State of art surgery	State of art surgery	None
Process VIP Patient	Lack of technology to ID VIP patients	Technology to ID VIP patient	Information technology

Figure 2: Healthcare case study value gap analysis

Based on this exercise, a sample student value gap analysis for their light rail system is shown in figure 3. The students effectively identified the value criteria to assess the current and future state, and the gaps that would define the need for the system.

Value Gap Analysis			
Criteria	**Current State**	**Future or Desired State**	**Gap**
Capability: Move train full of people between cities within a 15 minute period.	Track & train built. Currently takes 30 minutes from arrival at one city to arrival at the next.	Move train full of people between cities with a 15 minute period.	Need to shave 15 minutes off commute time. Full 30 minutes in current state includes waiting at station. Logistics need to be improved.
Function: Light Rail is in need of an electronic ticket sales system.	Paper tickets are currently sold at the train station via ticket machine. Long lines form at ticketing machines.	Fully electronic ticket sales system. Electronic ticketing system includes Light Rail member card that can be loaded with cash and swiped for paying at gate as well as internet web page where sales can occur.	Electronic ticket sales system needs to be designed and developed in order to reduce lines and improve upon overall logistics.
Value statement: Claim that the Light Rail is the safest form of travel between the three cities.	Currently the Light Rail is up and running with no mishaps.	It is desired that the Light Rail is accident free and the claim that it is the safest form of travel between the cities is true.	The Light Rail does not have a lot of history, however there is no room for learning about the safety of the system through trial and error. Safety improvements and alternatives need to be continually developed and implemented.

Figure 3: Student sample value gap analysis (Radon, N., Zhou, C., Wingfield, A., Gu Shuo, 2016)

Requirements and Architecture Phase 2:

The Requirements and Architecture phase of the lifecycle model is designed to gain information on the voice of the customer (VOC) to understand the needs of the customers and begin translating those customer requirements into the system's technical elements.

Use case diagrams are used to help generate customer requirements. A use case diagram for the case study is shown in figure 4 and the student's sample is shown in figure 5. The students' use case diagram demonstrated the understanding and ability to apply the tool. They identified appropriate use case scenarios in verb-noun format, and identified the actors that performed the scenarios. This was a more difficult tool that the students struggled with, until they saw the healthcare case study example.

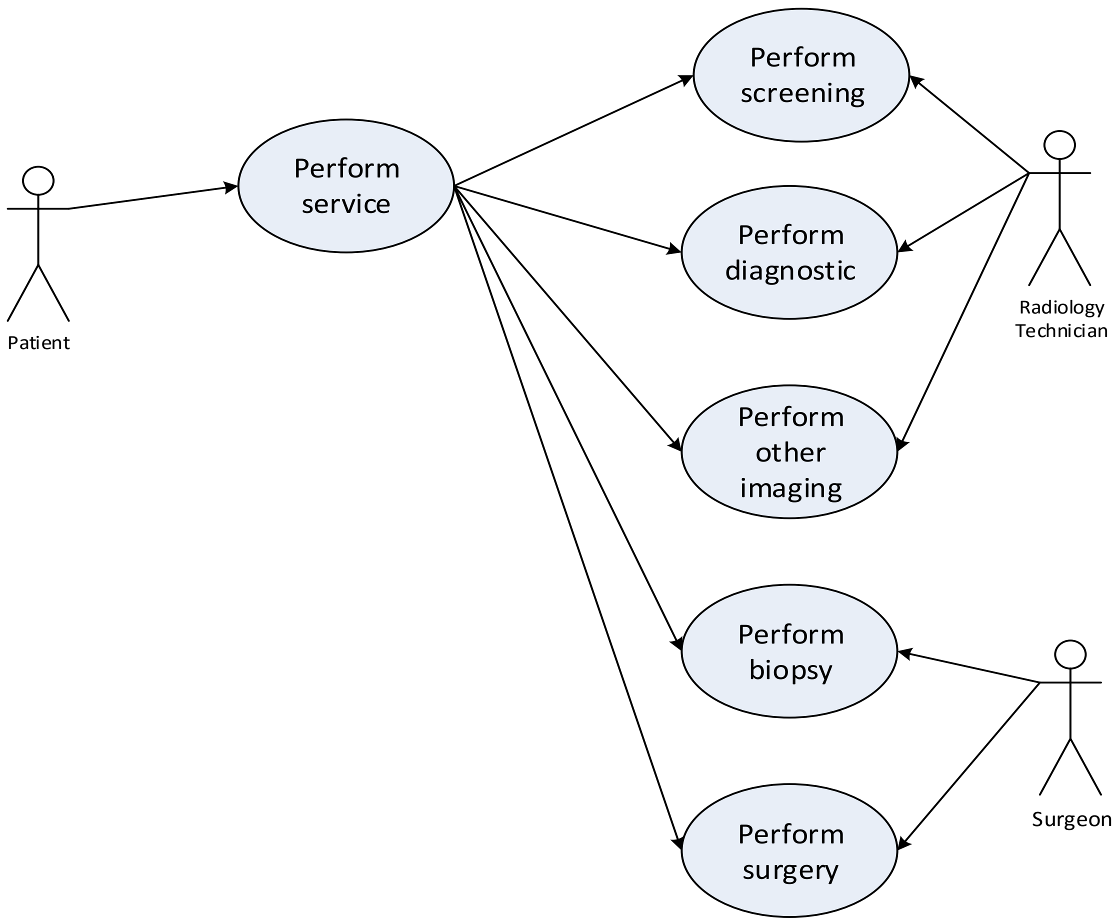

Figure 4 Healthcare case study use case diagram

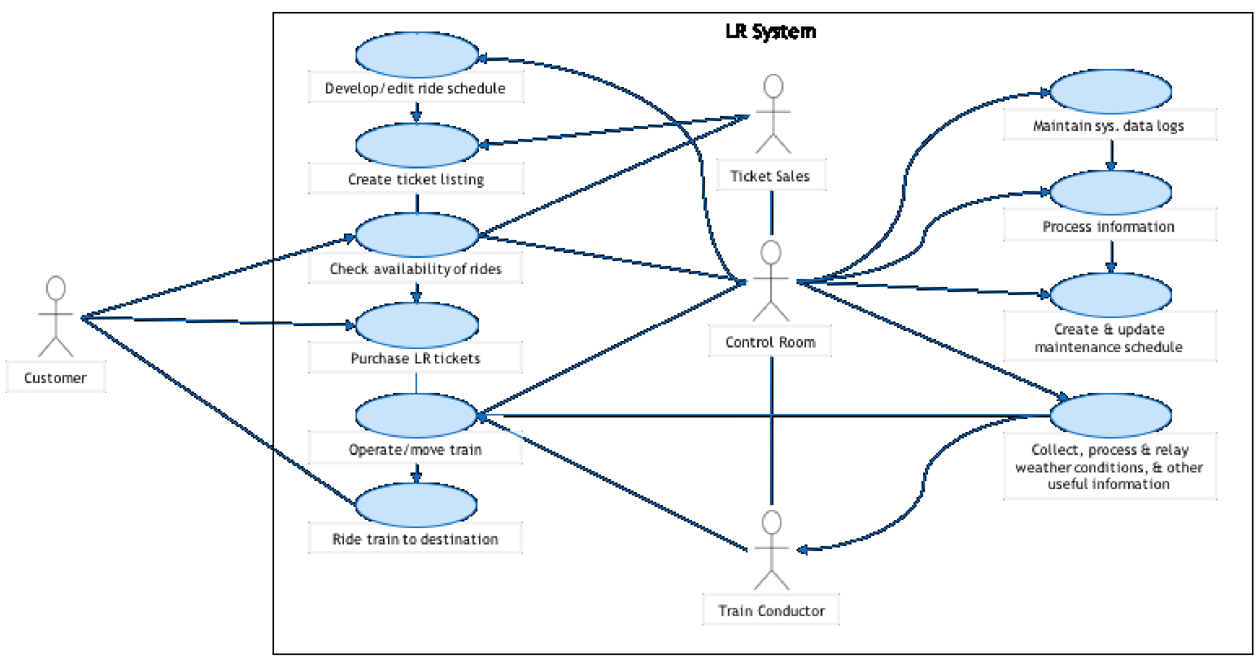

Figure 5 Student light rail system use case diagram (Radon, N., Zhou, C., Wingfield, A., Gu Shuo, 2016)

Detailed Design Phase 3:

The main purpose of the Detailed Design phase is to develop the detailed system design. The phase is also focused on understanding the factors that contribute to an efficient process and the potential root causes of inefficiencies so they are reduced or eliminated.

An important tool used in the design phase is a risk analysis. The healthcare risk analysis for the case study is shown in figure 6 and the student's sample risk analysis is shown in figure 6. The student example shows understanding and the ability to apply the risk analysis tool to their specific system that they are designing. Some of the other student teams struggled to differentiation between the risk event and the outcomes, but this team demonstrated a clear distinction between the elements of the risk analysis.

Risk #	Contributing causes	Risk Event	Outcomes	Impact
1	Recession economy	May not get donations that cover cost of construction of women's center	May not be able to provide new services as quickly as planned	Reduced revenue compared to plan
2	Regulatory requirements	Regulatory requirements may add to schedule	Need to spend over budget and extend the schedule	Need additional money to cover budget over runs
3	Technology availability	Software technology may not be available within schedule	Software functionality for patient navigator, an connecting to cancer center may not be available within schedule	Need to put in manual work-arounds

Figure 6: Healthcare case study risk analysis

Risk #	Contributing causes	Risk Event	Outcomes	Impact
1	Sharp turns, high speeds, bad weather (rain, snow, wind)	Cars could come off the track	Casualties, ruined train & track, serious safety issue, lost money	Panic, people may not want to ride. Cost, off schedule
2	Smoking, fireworks, Samsung phone, overheating engine faulty electrical	Potential failure	EMS comes out, alarms will go off, train will stop, doors open, water sprinklers	Panic, people may not want to ride, cost, off schedule, reputation of light rail goes down
3	Low security, low income area, high crime area, tightly packed crowd is easy target	Criminal activity	Stolen items, violence, police respond to scene of crime	Security cameras installed, reputation of light rail goes down
4	Old and or faulty tools, poor safety procedures / precautions taken	Injury of maintainer	Serious injury or potential death of maintainer, hospitalization, recovery time	Reputation of light rail goes down, lower credibility, doubtful maintainer crew

Figure 7: Student sample risk analysis (Radon, N., Zhou, C., Wingfield, A., Gu Shuo, 2016)

Implementation, Integration, Test & Verification Phase 4:
The purpose of the integration, test and verification phase is to pilot and/or implement the new system and assess whether the system is capable of meeting the desired requirements.
An n-squared diagram defines the system elements and how they interface. The case study n-squared diagram is shown in figure 8, and the student’s example is shown in figure 9.

Schedule Service	X	X								
	Authorize Service	X	X							
X		Process self-referral								
	X		Register Patient	X	**X**					
			X	Process VIP patient						
					Perform service	X	X	X	**X**	
					X	Connect to cancer center				
							Perform surgery			
					X	X	X	Provide results		**X**
					X				Provide spiritual care	
								X		Request records / film

Scheduling and Registration	**Services**	**Spiritual Care**	**Records**

Figure 8: Healthcare case study n-squared diagram

The students' n-squared diagram demonstrated understanding and the ability to apply the tool to their own system that they were designing for the course. They effectively defined how the pairs of system elements interacted, which is the goal of the n-squared diagram.

TRACK	Electrical power from track to train				
Train braking makes wheels stop on the track &train track selection will make track move	TRAIN	Signals from train to hardware such as braking, and track selection	Train functions are logged in a data file and interpreted by software	Departure and arrival times of the train will dictate future schedule	The number of seats in the train will limit the number of tickets sold
Support equipment and tools will determine status and condition of track	Support equipment hardware will determine state of functionality of train	HARDWARE	Functions of the hardware will be recorded in a data file and interpreted by software	Support equipment and hardware availability will have an effect on schedule	Cost and quality of hardware will have an effect on ticket prices
Software will determine the electricity levels in the track & determine if service is needed	Software will allow operation of control system used by the conductor	Software will control the interactions and movement of hardware through electricity	SOFTWARE	Software calculations & predictions aid in creating a reliable schedule	Software will allow sales of tickets
	Schedule will determine where and when the train travels	Tight schedule will determine amount of support equipment and tools needed	Software will change depending on changes in the schedule	SCHEDULE	Schedule will directly drive ticketing creation and sales
	Tickets sold will determine how many passengers will be on the train	Number of tickets sold will have an effect on how offer service on hardware components is required	Number of tickets sold will determine load on the software used for selling tickets	Number of tickets sold determines how tight the schedule is	TICKETING

Figure 9: Student n-squared diagram (Radon, N., Zhou, C., Wingfield, A., Gu Shuo, 2016)

Student Evaluation of Teaching Results:

The Student Evaluation of Teaching (SET) Results demonstrate that the students rated the course highly, as shown in Figure 4. The following questions were asked in the SET survey.
Q1: The instructor seemed organized.
Q2: I knew what I was expected to accomplish in this course.
Q3: The instructor presented the subject matter clearly.
Q4: The instructor created an environment that supported my learning.
Q5: The instructor generated a genuine interest in my success.
Q6: The feedback I received from the instructor improved my learning.
Q7: This course stimulated my interest in the subject.
Q8: This course increased my understanding of the subject.

Q9: I learned a great deal from this course.
Q10: I would recommend this course to other students.
Q11: I would recommend this instructor to other students.

A Likert agreement rating scale was used, from 1 – Strongly Disagree, to 5- Strongly Agree. Questions 8 and 9 best assessed the students' learning and these received high ratings of 4.7 and 4.6 respectively.

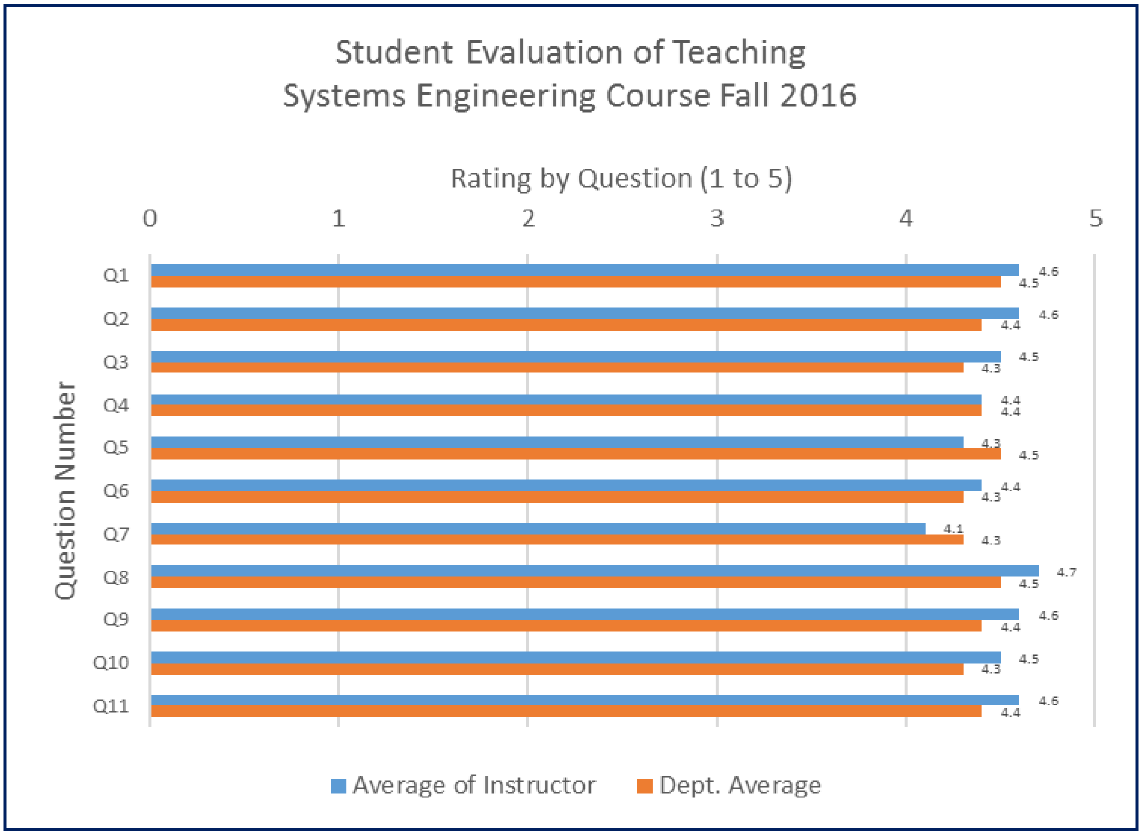

Figure 4: Student Evaluation of Teaching Systems Engineering Course Fall 2016

Conclusions:
The case study was very successful in enhancing the students' learning and application of the systems engineering tools and methodology, and in understanding the system design project's assignment expectations, as the case study survey results showed in the earlier section. The instructor assessed the students' ability to demonstrate knowledge of the systems engineering methodology and tools by performing active learning exercises and designing a system. They used the healthcare case study as a guide, and were effective in applying the tools and designing their own system based on using the healthcare case study as a guide. The University's Student Evaluation of Teaching (SET) survey results for this course were also high, demonstrating that the students believed that they learned the systems engineering material. The students also provided some constructive feedback that can help the instructor improve the case study for the future semesters.

Future Work:

The instructor can enhance the case study based on the results of the students' feedback from the fall semester. PowerPoint shows for a light rail system case study were developed by a former instructor. This material was used by the students as another example of use of some of the tools learned in the class. However, it lacked the comprehensive suite of tools that were applied in the healthcare case study and in the students' system design projects. The instructor can develop the remaining tools for this additional case study example, so that the students will have a different type of case study at their disposal to use as a learning strategy. Additionally, the instructor can research additional instructional strategies that may help the students more easily learn and apply the systems engineering principles. Since the theoretical principles can be more difficult because of their conceptual nature, the case study may not be the best method to enhance the theoretical principles learning.

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