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Applying Systems Engineering Tools to Teach Systems Engineering in an Engineering Management Program

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Abstract

Engineers learn how to design engineered solutions by applying their specialty engineering disciplines, such as chemical, electrical, mechanical, aerospace, materials, and industrial engineering to name a few. Systems engineering tools and concepts help to integrate the specialty engineering designs together to better design and manage complex systems. These same systems engineering tools can be used to teach systems engineering to engineers. A graduate-level engineering management curriculum includes a Management of Engineering Systems course, whose key learning objective is for the students to be able to synthesize and apply the systems engineering methods and tools to a real-world system design project. This paper will describe how the instructor applied systems engineering tools to enhance learning of systems engineering tools and concepts in an engineering management course. The students applied the systems engineering tools in the course to design a system in teams of 4 to 5 students. The instructor assessed the students on their ability to apply the systems engineering tools through the team reports. The average students' grades on their system design reports improved by 6% on the system engineering design reports assessments, from Fall 2016 to Fall 2017, and 5% from Spring 2017 to Fall 2017 (ANOVA alpha = 0.000181). However, the positive responses on the qualitative evaluation from the students' perspectives on the Student Evaluation of Teaching question "I learned a great deal from this course" decreased from Fall 2016 to Spring and Fall 2017 semesters by 16% (94% to 78%).

Keywords: Systems Engineering, Case studies, engineering management, engineering education

Introduction:

Engineers learn how to design engineered solutions by applying their specialty engineering disciplines, such as chemical, electrical, mechanical, aerospace, materials, and industrial engineering to name a few. Systems engineering tools and concepts help to integrate the specialty engineering designs together to better design and manage complex systems. These same systems engineering tools can be used to teach systems engineering to engineers.

The university's Department of Engineering Management, Systems, and Technology, in the School of Engineering teaches their Management of Engineering Systems, modeled on the Systems Engineering Body of Knowledge (SEBoK) (BKCASE Editorial Board, 2016). This body of knowledge represents "… a widely accepted, community-based and regularly updated baseline of systems engineering (SE) knowledge" (BKCASE Editorial Board, 2016).

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. The learning objectives from the course include the following:

- Articulate what systems engineering (SE) is and explain the importance of maintaining SE rigor throughout a system's life cycle
- Comprehend and incorporate different concepts, principles, and tools of systems engineering in solving problems and developing balanced system solutions
- Establish collaboration among all organizational functional areas necessary for effective systems engineering application
- Apply critical thinking to execute the SE process in realistic scenarios and projects and to defend your decisions and positions

This paper will describe how the instructor applied systems engineering tools to enhance learning of systems engineering tools and concepts in an engineering management course. The instructor developed a systems engineering framework that identified the systems engineering design activities, the tools and principles to be covered in the course. This framework provided a roadmap through the systems engineering design methodology for the students. An Excel-based Systems Engineering Tools Template (SETT) that provided many of the systems engineering tools for each phase of the system design methodology was developed that provides a standard template for the systems engineering tools to define the system concept and requirements, including a system project charter; risk, stakeholder, external, SWOT, internal, and value gap analyses; customer and systems requirements; and a process scenario template.

Teaching Methods and Instructional Strategies:

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. Information–providing type of learning typically uses lecture and demonstrations to convey information (Gentile, 2016). 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). 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). Cooperative methods are active learning techniques designed to teach collaborative skills (Gentile, 2016). Mastery-based methods are focused on providing a minimum mastery of the information. Finally, 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:

The following educational learning strategies were applied in the graduate-level engineering management systems engineering course: 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. When initially developing and deploying the course in the Fall 2016 semester the instructor incorporated several learning strategies, including:

- Traditional lecture PowerPoint presentations provided via the online learning website.
- Inquiry-oriented case studies including a healthcare case study and a light rail system case study.
- Active learning exercises incorporated into each class session.
- A cooperative team-based system design project.
- Creativity-inducing methods based application of systems engineering tools.

The instructor taught the course using the same learning strategies in the Spring 2017 semester. In Fall 2017, the instructor introduced an additional learning strategy developing an Excel-based Systems Engineering Tools Template (SETT) that provided many of the systems engineering tools for each phase of the system design methodology. This enhanced the active learning exercises, the case studies, and cooperative team-based system design project strategies. The instructor also developed examples of the systems engineering tools for the healthcare case study. Table 1 shows the Systems Engineering Methodology, Activities & Tools Framework (Furterer (2016a, 2017a)). This figure describes the systems engineering methodology and the activities performed in each phase. It also shows the tools taught in the class and applied by the students in their systems engineering research design case study. The principles applied in each phase are also shown. The tools incorporated into the SETT are bolded in Table 1. There were 34 students in the Spring 2017 course, and 31 students in the Fall 2017 course.

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: • **Strategic mission** • **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**	• Systems analysis • Wholeness and interactions

Vee Phase	Activities	Tools	Principles
		• Simulation Systems Analysis: • Selection criteria • 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 (Furterer, 2016, 2017)

Excel-based Systems Engineering Tools Template (SETT) Examples:

A sample tool from the Excel-based Systems Engineering Tools Template (SETT) for the system design phases follows. The instructor developed healthcare case study was used for the tools template examples.

Phase 1: Concept of Operations

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 from the Excel-based Systems Engineering Tools Template (SETT) was a value gap analysis of the proposed internal functions that a system could provide, to identify the system's mission. The healthcare system value gap analysis is shown in figure 2. The value gap analysis describes proposed internal functions to be included in the system, with an assessment of the function in the current state, and where the designers would like the system to be in the future. It also describes the gaps between the current and future state for each function. This example helped the students understand how to apply this tool.

Value Gap Analysis			
Internal 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 (Furterer, 2017)

Phase 2: Requirements and Architecture

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.

One of the examples for the healthcare case study tools was the operational definitions of the system metrics used to assess system performance and alignment between the customers and systems requirements, as shown in Figure 3. The operational definitions describe how the designers expect to measure the system and the effectiveness of the system design.

Operational Definition

Define a clear and concise description of the measurement and the process by which it is collected.

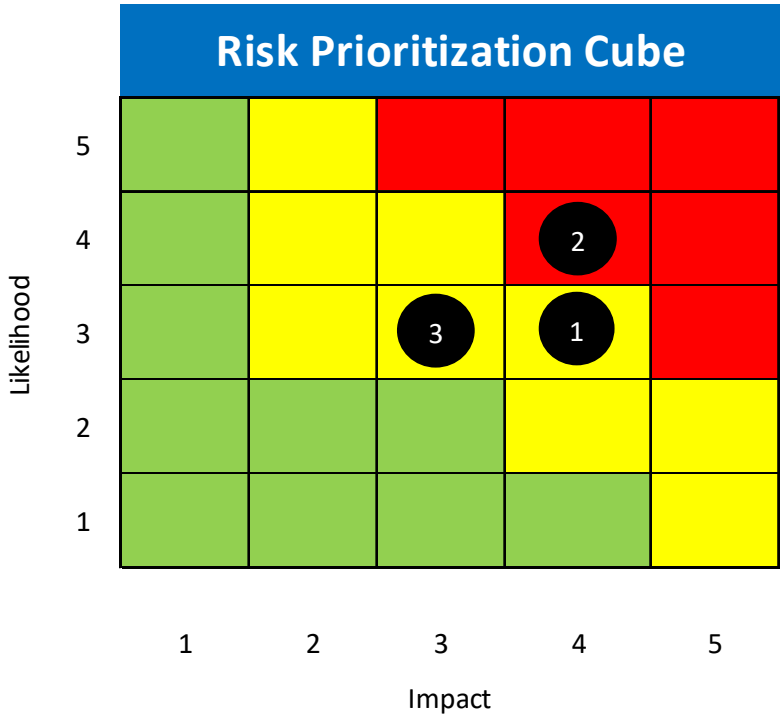
Operational Definition	Defining Measure	Purpose	Clear Way to Measure
Time from when patient goes into procedure room to when they leave	Procedure times by procedure type.	Identify issues with resources, and process issues that affect procedure time.	From Medical information System report
Time from when the patient is registered to when they get into the procedure room	Tracking wait times from registration until received into the procedure room.	Identify capacity issues with procedure.	From medical information system report
Time from when patient arrives in the facility to when registration is complete	Tracking time from when patient is logged into the registration system until the registration is complete at the front desk	Identify issues with resources, and process issues with registration.	From registration system report
Time to receive results of exam, from when you finished the procedure	Time it takes the patient to receive the exam results from their physician after the exam is complete.	To understand how long it takes to get results, and identify radiologist capacity constraints.	From imaging system report
Time to wait until get an appointment	Time it takes a patient to be able to get in for an appointment from when they request the appointment.	Identify issues with resources, and process issues for the entire imaging systems and processes.	From scheduling system report, implementing new fields to capture desired appointment time compared to actual appointment time

Figure 3: Operational definition tool example

Phase 3: 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 4. The Risk Prioritization Cube helps the designer to prioritize the potential system risks by their likelihood of occurrence and the impact of each risk, should they occur. This example prioritizes the number 2 risk of regulatory requirements possibly adding time to the schedule of the system design project.



Risk #	Risk Event
1	May not get donations that cover cost of construction of women's center
2	Regulatory requirements may add to schedule
3	Software technology may not be available within schedule

Figure 4: Healthcare case study risk prioritization cube

Phase 4: Implementation, Integration, Test & Verification Phase, Phase 5: System Validation

The purpose of the integration, test and verification and validation phases is to pilot and/or implement the new system and assess whether the system is capable of meeting the desired requirements.
A verification and validation test case example is shown in Figure 5. The test case provides detailed tasks that are performed to verify that the system works as it is designed and also validates that the system works as the users would like. The expected results are also identified so that the tests can ensure that the test cases pass or fail, and what actually occurs during the testing case.

Test Cases					
TASK #	TASK/STEPS	EXPECTED RESULT	PASS/FAIL	ACTUAL RESULT/DESCRIPTION	NOTES
Scenario 1: Schedule appointment					
1	Patient calls Central Scheduling and requests an imaging appointment	Central Scheduling answers phone and greets patient			
2	Ask for name, social security number from patient	Obtain patient information			
3	If Medical information file exists, verify demographic and update if necessary, if doesn't exist, create it.	Information verified or entered			
4	Ask patient which services would like to schedule for, could be multiple appointments	Patient provides list of services			
5	Ask patient if they have a preferred date and time of day	Patient provides preferred dates and times			
6	Review central schedule database for preferred date and time	Obtain appointment times			
7	Provide next available date and time	Obtain appointment times			
8	Confirm with patient, if not repeat steps 6 through 7	Appointment time confirmed (or start at task 6)			
9	Book appointments	Book appointment in system			
10	Provide prep information for patient	Provide prep information for patient			
11	Ask questions on test, procedure, insurance, other information	Patient asks questions			
12	Reconfirm date, time, remind patient to bring photo id, copay/deductible and script and provide any other instructions	Reconfirm appointment			

Figure 5: Healthcare case study verification test case

Phase 6: Implementation and Maintenance:

The purpose of Phase 6, Implementation and Maintenance, is to implement, deploy and maintain the system. The training plan is an important tool to plan how the operators will be trained to operate the system and perform the processes. A sample training plan for the healthcare case study is shown in Figure 6. The sample training plan provides a description of the training objectives, the training audience, and how the training will be performed.

Training Plan	
Develop a training plan of how the process changes will be rolled out to the stakeholders.	
Training Objectives and Outcomes:	Train on process improvement changes
Training Audience and Resources:	Medical Staff
Instructional Strategies	
Exercise and case studies:	None
Assessments and exams:	Director Assessment
Homework assignments:	None
Team and individual work:	Individual
Project work:	None
Presentations:	
Training mode:	*Live Classroom *Instructor Led *Train the Trainer *Other - Weekly update poster
Training schedule and syllabus:	Just-in-time training
Training location:	Conference room

Figure 6: Healthcare Training Plan Example

Assessment of Learning:

Instructor Assessment of Learning:

The instructor assessed the students' ability to apply the systems engineering tools through the evaluation of the systems design research reports. The average grades across the reports for the three semesters were 91% for Fall 2016 and Spring 2017, and 96% for Fall 2017. The students improved their ability to apply the systems engineering tools as evidenced by the instructor's evaluation of the students systems engineering design project reports. The reports included the tools and a written report describing the tools and the findings from the tools. The Excel-based Systems Engineering Tools Template (SETT) was used by all of the students for the tools that were included in the SETT to design their systems in Fall 2017. Although there are always uncontrollable factors including student demographics, attitude and motivation, this was the main difference in instructional strategies that the instructor controlled and changed during the Fall 2017 semester. It appears to have contributed to a statistically significant improvement in the ability of the students to better apply the systems engineering tools. The Analysis of Variance (ANOVA) statistical test was significant at an alpha of 0.000181. The Tukey confidence interval comparison graph showing the statistical difference between the systems engineering design report grades between Fall 2016 and Fall 2017, and Spring 2017 and Fall 2017 is shown in Figure 7. However, there is not a significant difference between the grades for Fall 2016 and Spring 2017, both prior to when the SETT was implemented. The Tukey comparison chart shows when the confidence interval does not cross the zero at the x-axis, that there is a significant difference between the two means on the y-axis.

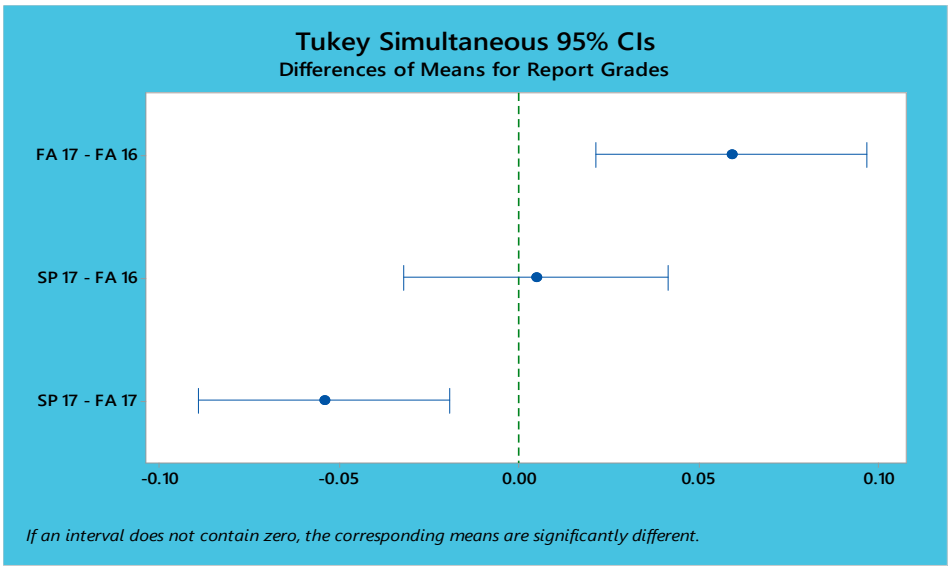


Figure 7: Tukey confidence interval comparison graph

Exam Questions Assessment to Evaluate Student Learning:

The instructor also used 2 exam questions to evaluate whether the learning was enhanced for two tools that were part of the SETT tool deliverables. The project charter and the n-squared diagram for defining the system interfaces were questions on the exam in Spring 2017 and Fall 2017. A 2-sample proportion test was used to compare the score that was converted to a percentage, since the number of students and points differed for each semester. For the project charter question, the Spring 2017 students (average grade of 97%), prior to the new SETT performed better on this question, than after the new tools deliverable Excel sheet was implemented in Fall 2017 (average grade of 86%). The 2-proportion test was significant at a 95% confidence level.

For the n-squared diagram, the Fall 2017 students (average grade of 100%) performed better after the SETT was implemented than the Spring 2017 students (average grade of 98%). The 2-proportion test was significant with a p-value of 0.024, for a 95% confidence level.

The assessment of just two exam questions may not accurately assess whether the entire SETT helped to enhance learning, so the instructor also used the student evaluation of teaching results described in the next section.

Student Evaluation of Teaching Results:

The Student Evaluation of Teaching (SET) Results demonstrate that the students rated the course highly, as shown in Figure 8. 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. Question 9 best represented the students' assessment of whether they learned a great deal in the course. Unfortunately, the percent of positive responses decreased from a high of 94% in the Fall 2016 semester to 78% in both the Spring 2017 and Fall 2017 semesters. The averages across all of the SET questions are provided for all three semesters from the SET data set, as shown in Figure 8.

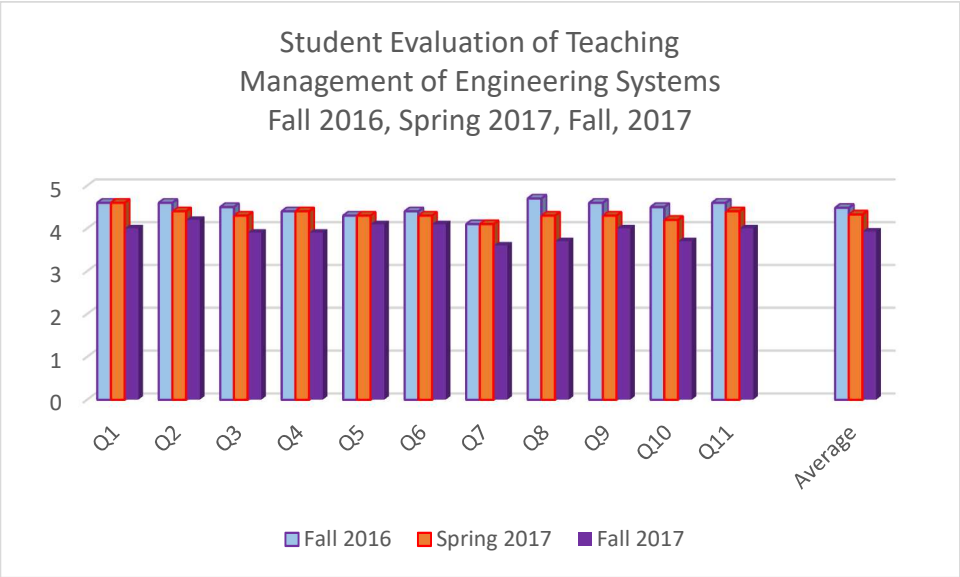


Figure 8 Student Evaluation of Teaching Management of Engineering Systems Course Semesters Fall 2016, Spring 2017 and Fall 2017

Reflection and Conclusions:

The Excel-based Systems Engineering Tools Template (SETT) was successful in improving the learning of students, and their ability to apply the systems engineering tools to design a real-world system, as evaluated by the instructor. The average grades improved by 5% and 6% from Fall 2016 and Spring 2017, respectively compared to Fall 2017 when the tools template was implemented.

However, the students' evaluation of teaching, decreased from the Fall 2016 to Spring 2017 and again in Fall 2017. The percentage of positive responses to the question "I learned a great deal from this course" decreased from a high of 94% to 78% in both the Spring and Fall 2017

semesters. The average scores across all of the questions also decreased from 4.5 in Fall 2016, to 4.3 in Spring 2017, to 3.9 in Fall 2017. These qualitative ratings by the students incorporate a broader spectrum of variables, including students' attitude, motivation, demographics, as well as other factors regarding the course. A key complaint from the students in the Fall 2017 semester was that they felt that the homework and exams that were done individually, were too redundant with the team-based system design project, and that there was too much out-of-class work. The instructor had broken the system design project into multiple reports in the Spring and Fall 2017 semesters, versus one report, and this could have contributed to the students' feeling overwhelmed and rated the course less favorably in the Spring and Fall 2017 semesters.

Future Work:

The instructor incorporated the feedback from the students from the Spring 2017 semester on the Student Evaluation of Teaching surveys into the course assessment strategy for the Spring 2018 semester. The instructor removed the homework assignments that were performed individually by the students to ensure that they were applying and learning all of the systems engineering tools, in the case that the teams divided up the work and tools on the systems design projects. The students will need to ensure that even if they aren't responsible for each and every tool on the systems design project that they still learn and are able to apply these tools. The exams will continue to assess the students learning on the applicable and most important tools. It will be interesting to see if the Student Evaluation of Teaching responses improve after this semester. The instructor will continue to enhance the course with additional instructional strategies to further enhance the students' learning and ability to apply the important systems engineering design tools.

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