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Introduction and Application of Lean Manufacturing Techniques in Mechanical Engineering Senior Design Practicum

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Abstract

Manufacturers have adopted lean manufacturing principles in order to reduce operating costs, decrease production time, and improve customer satisfaction. As lean manufacturing methodology becomes more commonplace in industry, introducing undergraduate students to these practices becomes increasingly important. This case study aimed to evaluate a module of a senior design curriculum and give undergraduate Mechanical Engineering students an introduction to lean manufacturing goals, tools, and best practices. This was accomplished through an in-class lecture, group discussions, along with pre and post surveys.

Survey results demonstrated that students were able to develop an effective understanding of lean manufacturing, could successfully identify wastes according to lean principles, and propose ways to implement lean tools and techniques on university-scale design projects. This allowed us to validate that students could apply lean manufacturing principles to a variety of prototype projects, giving them hands-on experience with lean practices. From the results of this study, a number of suggestions were recorded for implementing lean ideas thus improving the structure of a mechanical engineering capstone class. Incorporating these suggestions will enhance the efficiency of the course and provide students practical experience with lean manufacturing.

Introduction

Over the past 25 years, lean manufacturing methods and organization have become increasingly popular across a wide spectrum of industries. With such a strong shift to lean production, there is a clear need to prepare undergraduate students before they enter the workforce. A common definition for lean manufacturing, provided by the National Institute of Standards and Technology Manufacturing Extension Partnership's Lean Network, is "a systematic approach to identifying and eliminating waste (non-value added activities) through continuous improvement by flowing the product at the pull of the customer in pursuit of perfection" (Kilpatrick, 2003). The core idea of lean thinking is to maximize customer value through increased efficiency; every step in the production system is developed around the needs of the end consumer, reducing or eliminating non-value adding activities, called waste or *Muda* (What Is Lean, n.d). Lean production changes the focus of upper management from optimizing separate technologies to optimizing the flow of products and services through entire value stream (About Lean, n.d.). This process requires less human effort, less space, and less time to make products and services at lower costs, with fewer defects compared to traditional business systems (What Is Lean, n.d.).

Courses including lean are not widespread in higher education, and lean specific classes are almost absent from the curriculum (Fliedner & Mathieson, 2009). In the article *Lean on Campus: Lean Education Academic Network (LEAN) to Advance Lean in Academia*, George Taninecz states, “On the campuses of many colleges and universities, lean hardly shows up in undergraduate or graduate curricula and faculty fail or are hesitant to teach principles that business is embracing” (Taninecz, 2006). Engineering students entering the workforce are often unprepared to apply lean principles without further training. This forces future employers to incorporate lean manufacturing instruction in their operations, wasting time and money training new graduates.

Colorado State University, offers little training on lean manufacturing in any of the existing curriculum. None of the departments in the College of Engineering offer lean manufacturing classes prior to graduation. There is not an Industrial or Manufacturing program at Colorado State University, thus the Mechanical Engineering program was the best candidate at CSU to educate students on lean manufacturing and perform this research study. The capstone class of the Mechanical Engineering program at CSU is MECH 486, a class focused on a yearlong endeavor that incorporates the full lifecycle of an engineering design project. Students gain real-world engineering design experience by working in teams that simulate the technological environments of small, medium, and large-scale companies (Senior Projects, n.d.). The 2016-2017 year had nearly 30 projects for students to take part in, covering a wide variety of industry sponsored projects, intercollegiate competitions, and faculty sponsored projects. The majority of these projects focus on designing one-off prototype systems, new testing and research equipment, or making improvements to specific parts or components for industry sponsors, including CFD model development projects and controls system logic for vehicle systems. CSU also competes in a number of engineering collegiate competitions: the International Rocket Engineering Competition, EcoCAR 3, BAJA SAE, Formula SAE, and the Human Powered Vehicle Competition.

The primary goal of this study was to provide undergraduate Mechanical Engineering students in MECH 486 an introduction to lean manufacturing goals, tools, and best practices, and better prepare students for their future careers. A secondary goal was to validate that lean manufacturing principles can be taught to students in an introductory-level lecture, and then applied by students to a variety prototype projects.

Background and Literature Review

To begin this study, two publications were reviewed to develop baseline knowledge on lean manufacturing. The first was *The Machine That Changed the World*, a summary of a five year research study on the automobile industry and differences between Japanese and Western manufacturing styles published by Womack, Jones, and Roos in 1990. The researchers documented the principles underlying the Toyota Production System, which at the time was the most profitable automotive company in the world. Womack, Jones, and Roos were the first to define “Lean Manufacturing” and characterize the five principles of a “Lean Production System” to guide business, management, and engineering decisions (Womack, Jones, & Roos, 1990):

1) Specify value from the standpoint of the end customer by product family.
2) Identify all the steps in the value stream for each product family, eliminating every step, every action, and every practice that does not create value.
3) Make the remaining value-creating steps occur in a tight and integrated sequence so the product will flow smoothly toward the customer.
4) As flow is introduced, let customers pull value from the next upstream activity.
5) As these steps lead to greater transparency, enable managers and teams to eliminate further waste, pursuing perfection through continuous improvement.

The second publication used as a reference was *The Toyota Way*, written by Jeffery K. Liker in 2004. The book explains Toyota's unique approach to Lean Management and 14 management principles that drove their quality and efficiency focused company culture. The work gives valuable insight into the fundamental principles of a lean corporation, and how many of those principles can be applied to any organization, in manufacturing or elsewhere. The book also describes some of the pitfalls of implementing some, but not all, of the principles of lean culture (Liker, 2004).

Additional literature and a number of studies covering the implementation of lean in higher education settings were reviewed to develop methods for constructing lecture and surveys. The ASEE article *Trends in Manufacturing Education: An Educator's View* (Jack & Hawks, 2012) illustrates that articles on Lean Manufacturing and Lean Six Sigma are being published on this subject matter at an increasing rate. There were only five ASEE papers published on Lean or Six Sigma prior to 2001 however there were 41 published between 2002 and 2001. Dr. William Balzer's 2014 book *Lean Higher Education: Increasing the Value and Performance of University Processes* documented many instances where lean methodology was implemented in higher education, and contained practical advice, case studies, and theories about how Lean should be implemented in higher education. The research included the psychology of lean systems, performance appraisal, job attitudes, and applied decision making (Balzer, 2010). *Lean and the Learning Organization in Higher Education* by David E. Francis (2014) reviewed possibilities for how lean principles could be applied to university education. It focused on institutional applications and methods for an entire university to incorporate lean initiatives. Francis presented recommendations for organizations considering or pursuing lean implementations, or further enhancement of organizational learning. Dragomir Cristina and Surugiu Felicia's *Implementing Lean in a Higher Education University* presented three case studies of implementing lean in UK and USA universities, and described how those case studies could be useful examples for implementing lean in any university environment (Cristina & Felicia, 2012). The research by Sreedharan & Liou (2007), *Can Lean Manufacturing Be Applied to University Laboratories,* illustrated the benefits of enhancing student learning of lean manufacturing in the university environment. This case study implemented lean manufacturing principles in the Laser Aided Manufacturing Processes (LAMP) Lab at the University of Missouri-Rolla. The approach began with the application of value stream mapping to the labs manufacturing process, then creating a future state map to create an ideal process, and finished with the implementation of 5S in the laboratory. Results showed an improved process and a cleaner, safer, more organized laboratory (Sreedharan & Liou, 2007). Using these published works as a guide, this case study attempted to provide a solid foundation of knowledge on lean manufacturing to students and then have them implement those teachings in small scale prototype projects.

Methods

This case study took place during the fall and spring semesters of the 2016-2017 academic year. The subjects of this research study were students enrolled in the Mechanical Engineer Senior Design Practicum - MECH 486 which included senior engineering students from both the Mechanical Engineering (ME) and Electrical & Computer Engineering (ECE) departments at Colorado State University. This was the only requirement to participate; no further training or experience was necessary. There were 182 students total in the class, approximately 81% male (148) and 19% female (34). Students' ages ranged from 21 to 45, with most under 25 years old. The class was made up of 95% ME students, the remaining 5% of students coming from the ECE department.

Jamison Bair, the researcher performing the study, one of three teaching assistants for the class, was responsible for grading written deliverables and providing guidance to a portion of the senior design teams. Mr. Bair prepared and administered all of the surveys, as well as delivered the lecture on lean manufacturing to the class. Participation in the research study was voluntary; however, students that completed both surveys and attended the lecture given in class were awarded extra credit in the participation portion of the class grade by submitting a screenshot of the confirmation when completing the surveys in the class Canvas website. Of the 182 students in the class, 155 (85%) students completed the preliminary survey, 141 (72 %) attended the in class lecture, and 98 (54%) completed the second survey. Students were asked to submit the last four digits of their CSU student ID number in the surveys to allow the researcher to compare the pre and post surveys while keeping the survey anonymous. The ID numbers were checked for duplicates when analyzing data, and no duplicates were found. Students used I-Clickers associated with their student IDs to record attendance at the end of lecture. By comparing the student ID numbers in the survey responses and the I-Clicker attendance from the day of the lecture, it was found that a total of 98 (54% of class population) students completed both surveys and attended the lecture.

The study began with an initial online survey that gauged students' preliminary knowledge on lean goals, tools, and practices. The preliminary survey contained 10 open and close ended questions, created and delivered using Google Forms. The survey questions were developed using Bloom's Taxonomy, first defined in the *Taxonomy of Educational Objectives* in 1956. The taxonomy was developed to increase critical thinking and improve understanding, not only through high-level knowledge based questions, but through active application of the information to ensure comprehension (Bloom, 1956). The first survey addressed the lower levels of the taxonomy while the second survey questions were focused on application and corresponded to the higher levels of Bloom's framework. The first survey questions are listed below:

1) On a scale from 1 - 10, how would you rank your understanding of lean manufacturing?
2) Have you ever worked in or for a company that implemented lean manufacturing?

3) Have you ever taken a course/class/training where you were informed about lean manufacturing?
4) What are the 5 major goals or principles of lean manufacturing?
5) What does 5S stand for?
6) List 4 types of waste identified in Lean Manufacturing.
7) In your own words, describe the concept of value stream mapping.
8) According to lean manufacturing principles, what is value? Who defines value in this context?
9) Describe the difference between push and pull manufacturing.
10) List three ways your senior design projects could use lean manufacturing tools/ techniques.

Open ended answers were reviewed and marked as either correct or incorrect in an objective manner. Answers that contained at least a significant portion of the correct answer were marked as correct. The questions that received no response were marked as incorrect, as there was not a time limit when taking the survey and the survey was formatted in a method where it was impossible to submit the form without scrolling to the bottom after viewing all questions. This eliminated the possibility of students missing or not answering questions unintentionally.

Following the introductory survey, a presentation on lean manufacturing took place in class during the regular scheduled lecture time for MECH 486. The lecture was approximately 90 minutes, with two short discussion sessions (5-10 minutes) between students and teams at different points in the lecture and a final discussion session among senior design teams.

The presentation gave a thorough introduction to lean manufacturing as defined by Womack, Jones, and Roos. It then covered the history and development of lean manufacturing, beginning with the works of Eli Whitney and the standardization of parts in the 1860's, Fredrick Taylor's studies on workplace efficiency, standardized work and scientific management in the 1890's, and the Ford Production System's novel concepts of the assembly line, manufacturing strategy sequence, conveyor systems, and flow style production in 1910 (Shternberg, 2011). The lecture then covered the background of the Toyota Motor Company and its early pioneers, Eiji Toyoda, Taiichi Ohno, and Sakichi & Kiichiro Toyoda.

The presentation then discussed the basic ideas of the Toyota Production System, including an explanation of its process and underlying philosophy. The lecture described the Toyota House of Quality, including Just-In-Time and *Jidoka*, as well as the foundation of continuous improvement (*kaizen*), established processes (*andon*, *kanban*, and *heijunka*), standard work, and total employee involvement.

After a thorough introduction to the foundations of lean established by the TPS, each of the 5 principles of lean manufacturing were presented to the students in greater detail. Examples of value stream maps (Shternberg, 2011) and definitions of value vs. non-value adding activities were given. A group discussion took place covering examples of value added and non-value added activities that each senior design group experienced. The lecture continued with the 3rd principle of lean and covered sequencing activities, bottleneck identification, and the theory behind TAKT time, progressing to the concept of pull-style manufacturing and its major differences from the push-style of manufacturing typically seen in a mass manufacturing environment. This section also elaborated on *kanban* signals, a lean tool developed in the TPS to better manage inventory and signal the need for additional materials and supplies, reducing overall inventory. Finally, the principle of the continuous pursuit of perfection was explained in further detail, and examples were given to students. The lecture focused on building a "Lean Culture" from both management reorganization and the engagement of all employees, the Five Why's of the TPS, Design for Six Sigma, quality and customer management, and process monitoring (Womack & Jones, 1996).

After the 5 principles of lean were defined, the lecture covered the 8 types of waste addressed in lean manufacturing; Defects, Overproduction, Waiting, Not Utilizing Talent, Transportation, Inventory Excess, Motion Waste, and Excess Processing. These 8 wastes were selected due to the helpful mnemonic DOWNTIME, to aid students in remembering the various types of waste. A second discussion occurred afterwards, and students presented examples of waste they encountered in their own projects.

The final portion of the lecture gave examples of real world tools and techniques used in lean corporations, with a major focus on 5S. Additional tools discussed were Total Productive Maintenance (TPM), Standardized Work, Load Leveling, *Jidoka*, *Kanban*, and Single Minute Exchange of Dies (SMED). This was to broaden the student's vocabulary of lean terminology, and to engage them in thinking critically about how these techniques were applicable to their own projects. The lecture ended with a review of the materials, and afterwards students were divided into their respective senior design groups and tasked with identifying the value stream for their project, areas where they can reduce wasted effort, and with developing at least one action item they can perform to address each of the 5S organizational methods.

A second online survey was released roughly a month after the lecture to evaluate information retention, effectiveness of the lecture, and assist the students in applying the principles of lean manufacturing to their projects. The post-survey questions were similar to the preliminary survey, but had students elaborate on the applicability of each in their senior design projects:

1) On a scale from 1-10 how would you rank your understanding of lean manufacturing?
2) On a scale from 1-10 how beneficial was the introductory lecture given on lean manufacturing?
3) Do you have any suggestions for improving the lean manufacturing lecture?
4) List and give a brief definition of the 5 principles of lean manufacturing."
5) What are the 5 steps in 5S? Give an example of how your team could apply each of the steps in your project.
6) List the 8 types of waste addressed in lean manufacturing.
7) Identify three types of waste related to your Senior Design Project and at least one way to minimize that type of waste.
8) Describe the concept of value stream mapping. List at least 5 value adding steps for your project.
9) According to lean manufacturing principles, what is value? Who defines value in your

project?

10) Describe the difference between push and pull manufacturing. List three benefits of pull style manufacturing.
11) List three ways your senior design projects could use lean manufacturing techniques.

The first questions allowed the researchers to evaluate quantitatively and qualitatively the improvement of the students' knowledge on lean, using a linear scale with results corresponding to Likert style responses (1 = No understanding/benefit, 5 = baseline understanding/ somewhat beneficial, 10 = extremely knowledgeable/beneficial). The next two questions judged how beneficial the students found the lecture, as well as to critique effectiveness so that an evaluation of the teaching method could be performed. Student responses were categorized according to answer, and suggestions were ranked in order of popularity. The latter questions reviewed the major concepts that were covered in lecture to reiterate the information from the lecture, and to apply the concepts covered to the students' projects. Question 4 was repeated from the preliminary survey, and tested students' ability to correctly recall and define the 5 principles of lean. Students then elaborated on what they learned about the 5S methodology and were asked to apply the 5S steps to their project. Questions 6 & 7 addressed identification and elimination of waste to ensure that students learned the types of waste defined by lean methodology and demonstrate they could identify areas in which their senior design projects wasted time and resources. The feedback from these responses was grouped by the most common answers, including the 8 categories taught in lecture, as well as wastes that were applicable to student projects but did not fall into one of the major categories. Post-survey question 8 allowed students to show that they could identify non-value adding activities and value adding activities, and construct a value stream map. Question 9 had students reflect on the basic idea that customer defines value, and is the driving factor for many engineering decisions. The second part of the question had students think critically about who the final "customers" are in their respective projects. Question 10 covered push versus pull style manufacturing, intended to check student comprehension of the differences. The latter part of the question had the student analyze pull-style manufacturing and list three benefits as compared with a batch-style manufacturing process. The final question on the second survey was the same as in the first survey, to verify that students were able to better identify ways they could implement lean manufacturing tools and techniques into their projects, and to have students realize the benefits of this implementation.

The survey results from the pre and post surveys were analyzed both independently and in conjunction to illustrate the changes in student understanding after the class lecture. This included filtering results of students that did not attend lecture, categorizing responses based on popularity, and tracking the difference between pre and post surveys.

Results

The results from the pre-lecture and post-lecture survey showed a large improvement in lean manufacturing understanding. The preliminary survey showed a lack of training and prior knowledge on lean fundamentals, leading to a lower quality of answers regarding implementation. Of the 155 students that took the first survey 131 students did not have any sort of training in lean, either in the CSU curriculum or through training received while working in industry. Only 30 students had worked in a company that incorporated aspects of lean manufacturing. 30 students were unsure if the company they worked at incorporated lean manufacturing, indicating their understanding of lean was not developed enough to recognize it. Of the 30 students that said they had worked in a lean workplace, only 10 received official training on the subject.

This lack of training both in industry and in higher education was also supported by the fact that of the 23 students that stated they have received training on lean manufacturing, 13 answered “No or Unsure” when asked if they had worked in a company that incorporated lean manufacturing. This means that of the 155 students that participated in the survey, only 8% received an education on lean fundamentals outside of working in industry.

The first survey responses were analyzed to identify areas of lean manufacturing where students had the least amount of background knowledge and understanding. The table below shows the percentage of correct responses from the students that took both surveys and attended the lecture so a comparison could be made to the post survey. Students had a stronger grasp on the concepts of values stream mapping, identifying customer value, and the difference between push and pull manufacturing compared to wastes identified in lean production, the five principles of lean, and the popular tool of 5S. However, even the question answered the most times correctly, only 30.8% of the students were correct. The average percentage of questions answered correctly was 20.7%.

Table 1: Pre-Survey Percentages of Correctly Answered Questions

Questions on Lean Principles from Lean Manufacturing Survey #1	**% of Students Answering Question Correctly (98 Responses)**
According to lean manufacturing principals what is value? Who defines value in this context?	30.8%
In your own words describe the concept of value stream mapping.	26.5 %
Describe the difference between push and pull manufacturing.	22.4 %
List 4 types of waste identified in Lean Manufacturing.	18.4%
What are the 5 major goals or principles of lean manufacturing?	15.4%
What does 5S stand for?	11.2%

In the first survey only a small number of students were able to apply actual lean manufacturing ideals to their project. Most of the responses stated that teams could reduce material waste and scrap, design for easier manufacturing, or make cost effective decisions when procuring materials. Additional responses also included being more environmentally conscious, making lightweight designs, and planning more effectively.

Overall, the results from the second survey demonstrated that comprehension was much improved when compared to the preliminary survey. Students answers to the knowledge and comprehension based questions on lean manufacturing was improved in every category that was presented in the pre-survey and lecture. Students also developed a number of ways that lean manufacturing techniques could be applied to their projects. Students stated the lecture was very beneficial and their self-ranking of lean understanding increased dramatically. Results from the post survey questions can be seen below and are ordered by the highest scoring sections.

Table 2: Post Survey Percentages of Correctly Answered Responses and Improvement from Preliminary Survey

Questions from Lean Survey #2	**% of Students Answering Question Correctly (98 responses)**	**% Improvement from Pre-Survey**
Describe the difference between push and pull manufacturing. List three benefits of pull style manufacturing.	76.5%	54.1%
According to lean manufacturing principals what is value? Who defines value in your project?	73.4%	42.6%
List the 8 types of waste addressed in lean manufacturing.	72.4%	54%
What are the 5 steps in 5S? Give an example of how your team could apply each of the steps in your project.	71.4%	58.2%
List and give a brief definition of the 5 principles of lean manufacturing.	69.4%	56%
Describe the concept of value stream mapping. List at least 5 value adding steps for your project.	63.3%	36.8%

Question six from the post survey asked students to identify three types of waste related to their senior design project, and suggest and at least one way to minimize that type of waste. The answers were categorized as seen Figure 1 and provided a very clear glimpse of the major wastes students experienced in the Senior Design curriculum.

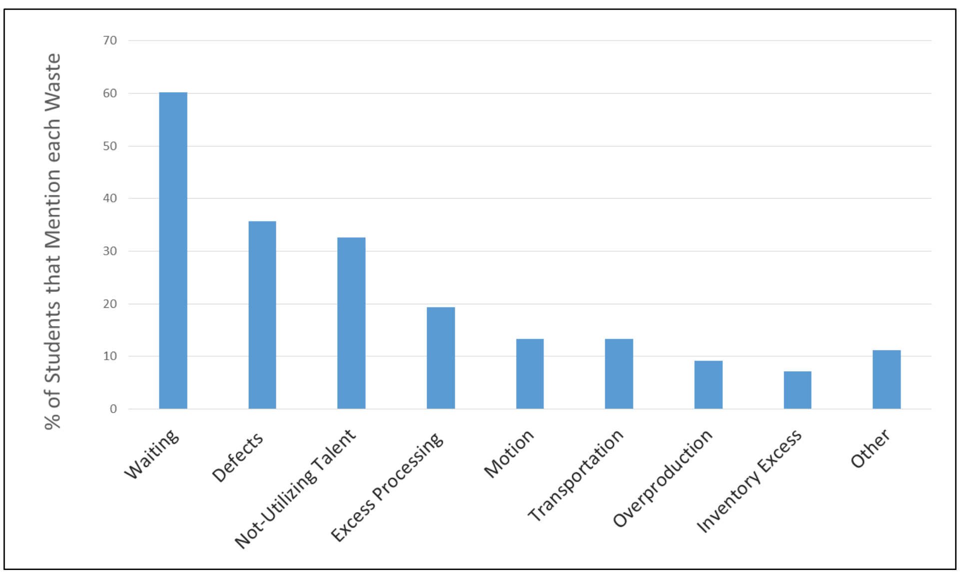

Figure 1: Most Popular Wastes Identified by Students

Many of the answers categorized under “Waiting” focused on time wasted due to poorly defined tasks, lack of parts or materials, and difficulty locating tools, equipment or information. One student stated “Waiting on feedback from advisors and instructors: Ask the instructors and or advisors to be more responsive and grade assignments in a timely manner with useable feedback to facilitate learning.” This illustrates that much of the time spent waiting is not necessarily the fault of the students and could be improved by better management from the teachers and advisors of the class. 38% of students identified “Defects” as a major source of waste. All senior engineering project involve trial and error, but minimizing major production defects would greatly improve efficiency in senior design. One student stated project sponsors “know our plans and we spend hours pursuing them, then once it's done they say it won't work based on their own experience. Tell me before so I don't waste hours doing something pointless.” Issues like this are common in senior design because sponsors allow students to solve the problems on their own, even if it is has been shown to be incorrect in the past. The other common answer in the identification of waste question was not utilizing talent. This was identified by approximately 34% of all the students. One student said “Some team members are not vocal about their strengths so it took most of fall semester to determine who should be working on what. Now that talents have revealed themselves tasks can be divided in a more efficient manner.” Additional responses included dividing tasks based on tasks and availability, assigning the correct number of people to a particular job, and “intellectual waste” by allowing the ideas from non-vocal team members go unheard.

Other beneficial responses to the waste identification from other categories included excess processing, transportation, and motion. One student provided a great response on excess processing: “Most team members use Solidworks, but Airframe/integration uses Creo, so time is wasted transferring CAD to another file type or program. A particular CAD type should be specified, initially.” Other answers included transportation wastes while working between multiple campuses, making multiple trips to the hardware store, and by procuring parts from local vendors to cut down on lead times. Motion waste was identified by 13 students, most responses focused on looking for tools and information as well as traveling to and from different campuses. One interesting motion waste was identified by a team working on the controls and modeling system for a hybrid electric vehicle. The team builds models in a simulation environment and then must transfer the models into a slightly altered hardware simulation. The software they use has the ability to automatically link the two models. “By linking the SIL (Software in Loop) and HIL (Hardware in Loop) transition properly we won't have as much work when moving one model to the other.” This illustrates that even in a project that does not involve manufacturing, wastes can still be systematically eliminated by developing better processes.

There were two major questions regarding implementing lean in senior design, the first had students explain how they could implement each of the steps of 5S in their project. Below is a list of the five steps in 5S and a few associated ideas that students developed for each.

1) **Sort -** Eliminate hard to manufacture components, eliminate unnecessary logic in controllers, better management of tasks based on timeline and schedule, eliminate tests that do not need validation by experiment, reducing scope creep.

2) **Set-** Organizing tools in easy to access locations, labeling equipment and storage locations, having parts laid out prior to beginning manufacturing or assembly, reducing clutter in high traffic work areas, creating tooling boards with outlines for each individual tool, consolidating information into a single location (i.e. using Google Drive vs the CSU T:// drive), having established meeting agendas for all team meetings.
3) **Shine-** Cleaning and organization of working area on a regular basis, performing preventative maintenance on most used equipment, methods of tracking version control on documentation, archiving old files and documents when no longer needed.
4) **Standardize** - Using the same types of hardware & fittings, creating well documented procedures, creating well defined responsibility matrixes and project tracking tools, using standardized templates for part drawings and manufacturing instructions, following specific ASTM and ASME standards for testing and manufacturing, selecting the same types of fasteners (SAE or Metric).
5) **Sustain** - Tracking processes on monthly basis and continuing to make improvements, creating methods to keep students accountable for standardized tasks, maintain the clean workspace by having weekly 5S audits, create documentation with the most important information and tricks and tips that can be used by all team members, create handoff documentation for projects that will continue next year that will improve knowledge transfer to next year's teams.

The second question in regards to implementation had students brainstorm three ways they could utilize lean in their projects. Though many students only listed ways that implementing lean would benefit their project such as “eliminate waste, reduce cost, and shorten lead times” the majority of students were able to come up with actual techniques for implementation. The responses were grouped into similar categories, mostly ideas and topics discussed in lecture. The three most popular answers were identifying and eliminating waste, implementing 5S, and becoming more customer focused, three core ideas of lean thinking.

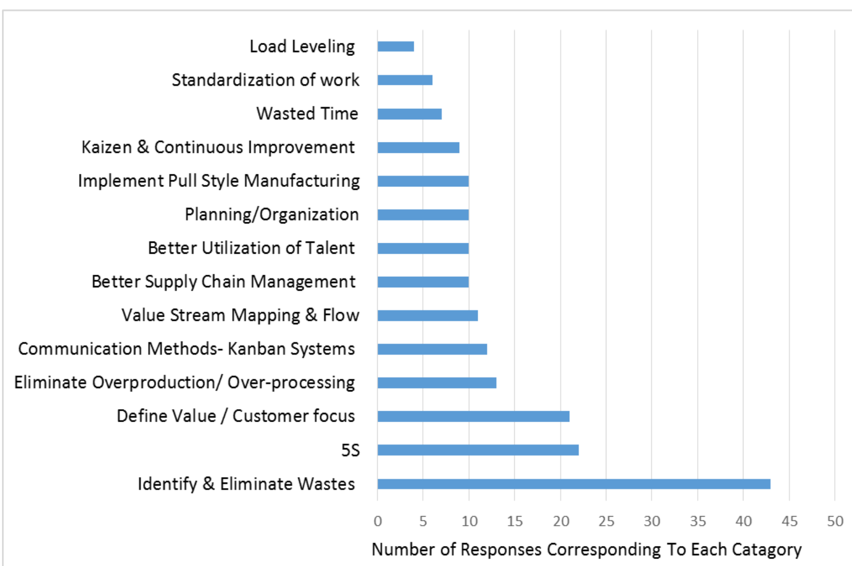

Figure 2: Responses from Students on Implementing Lean Techniques in ME Senior Design

Nearly 60% of students, stated that identifying and attempting to minimize waste was the best way to implement lean. This was a generic answer but indicates that the majority of teams felt like they could actually make a conscious effort to eliminate steps and activities in their project that do not deliver value to the end customer.

The next most common answer was implementing 5S organizational methodology within the teams. From the survey responses it seems that all projects could implement 5S in a number of different ways, even if the project was not manufacturing focused. Teams working on a wide variety of projects all felt that the teams could be better organized both in their workspaces as well as with document control, management methods, and process documentation and execution.

Defining value early in the project increased emphasis on the customer. It was evident that many groups were not given well defined customer requirements at the beginning of their projects, leading to wasted effort on unimportant tasks. Knowing the most important areas of focus beforehand allowed the teams to better direct their efforts, and establish quality criteria early in the design process.

About 13% of students reported that implementing *kanban* style visual reporting systems increased their efficiency. Much of the previous waste was due to poor communication, both in terms of project planning and the need for materials and supplies. By implementing *kanban*, teams could delegate and plan future item procurement much more efficiently. Many students observed that establishing procurement plans would reduce problems with long lead times.

Another technique students felt would be beneficial was creating value stream maps in the planning and design phases. Streamlining the project flow would eliminate many forms of waste if the process was outlined and approved by advisors in advance. Since the students are often unfamiliar with the tasks associated with their projects early on, creating a “living” value stream map to be continuously updated would allow teams to better plan around the flow of materials and information from sponsors, vendors, and advisors.

Other ideas for implementation included *kaizen*, the principle of load leveling and standardizing work. Students stated that implementing *kaizen* ideals, and creating systems to self-reflect and self-correct on various processes, would be beneficial. A common observation was that, due to uneven workflow, reports and deliverables were often prepared just before they were due. Leveling workload by gradually developing reports throughout the semester would dramatically reduce these stresses. Another student proposal was standardizing work for all team members. Through documenting best practices and procedures, all team members could be kept up to speed on different aspects of the process. Students also included standardization suggestions for meeting agendas, file naming conventions, and lists of distributors and vendors. This would be particularly important for multi-year projects, ensuring effective knowledge and documentation transfer between teams.

The results from the pre and post surveys and students’ self-rankings of their understanding were compared to assess the effectiveness of the lecture in teaching lean fundamentals. The second survey showing an average correct answer rate of 71% compared to 20.7% in the preliminary survey. Figure 3 shows each question topic and the improvement from the pre to the post survey.

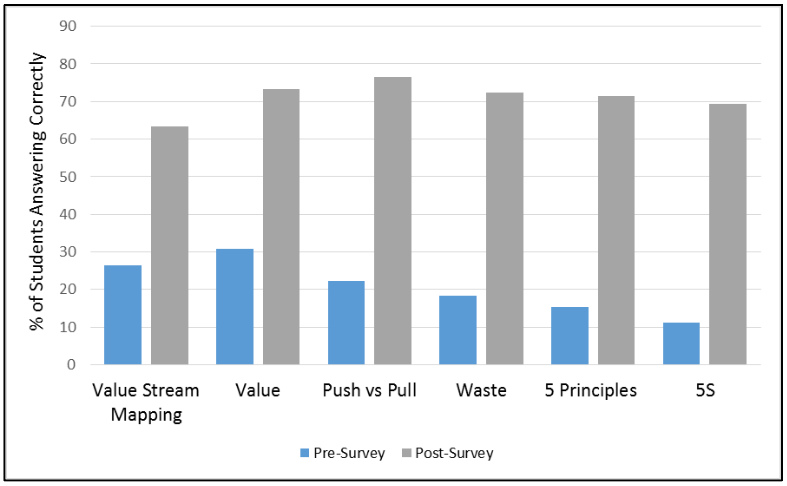

Figure 3: Comparison of Correct Responses between Pre and Post Survey

A second comparison made was between students' ranking of their own understanding of lean manufacturing before and after the lecture and can be seen in Figure 4. In the preliminary survey, 33% of student responses ranked their understanding at 1, indicating no prior education on lean manufacturing, 69% ranked their understanding at 3 or less, and only six students, less than 4% of the class, ranked their understanding at 8 or above. The average ranking of the preliminary survey for all students was 3.1, with a standard deviation of 2.25. With a few exceptions, the majority of students had little preliminary understanding of lean.

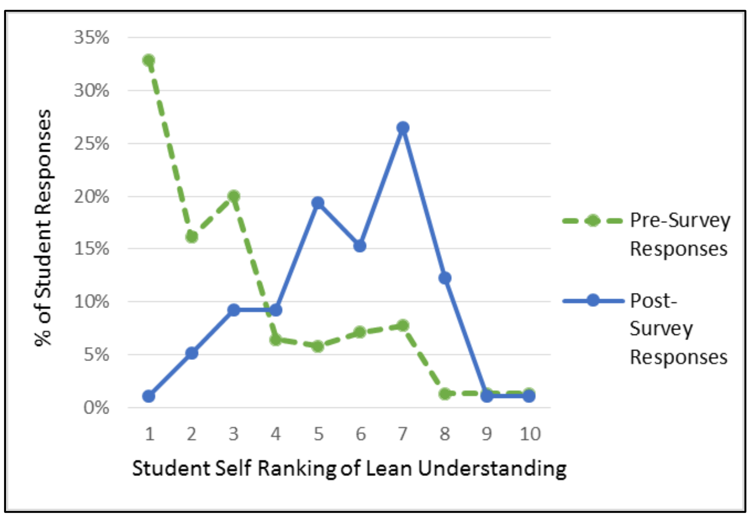

Figure 4: Comparison of Students Pre and Post Survey Self Ranking of Understanding

In the second survey, the average score of student responses improved to 5.7. The standard deviation also decreased to 1.84, which means that a large portion of students gained at least some understanding of lean ideas. Only 15% of the students ranked their understanding of lean below 4. A score of 5 was considered to be a solid foundation of lean manufacturing knowledge, which means the majority of the class achieved an adequate level of knowledge. Many students said in their survey feedback that they went from having "no background on lean manufacturing" to "having a good foundation of knowledge", emphasizing how quickly lean fundamentals can be taught.

Finally, students were asked to rank, from 1-10, how beneficial the lecture was to them. The results show a large distribution of answers; however, the majority of students felt the lecture was very beneficial. The cumulative total of answers greater that 5 was 88% of students. This indicated that the majority of students felt that the lecture was "somewhat beneficial" to "very beneficial".

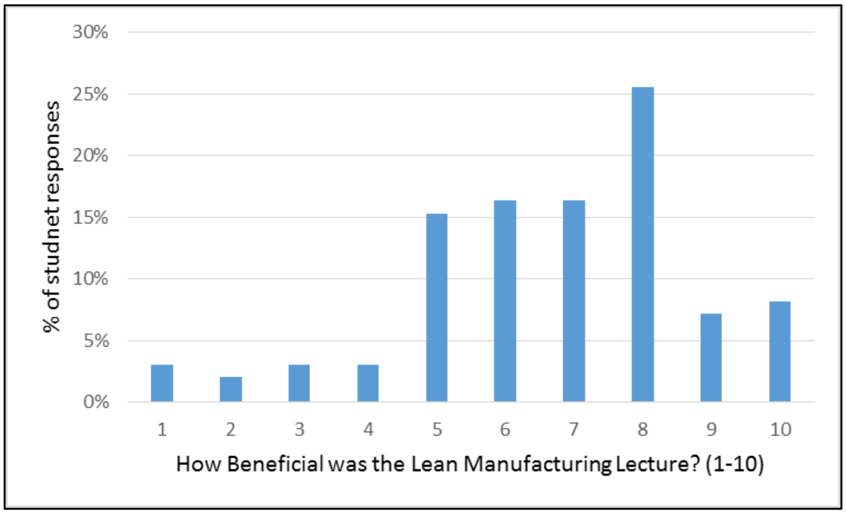

Figure 5: Student Responses on Benefit of Lean Manufacturing Lecture

From the responses involving suggestions to improve the lean manufacturing lecture, a number of areas for improvement were noted by the researcher. Many students mentioned engaging the class further with more use of the I-clickers would create positive feedback loops between instructors and students, enhancing communication and maintaining student involvement. The use of case studies to communicate ideas and principles of lean manufacturing would give students tangible instances to refer to in comprehending the material. Additional work beyond the survey, such as a quiz or paper, would reinforce the teaching through practice, and multiple lectures would give students more opportunity to grasp the material was also mentioned by a few students. Further use of pictures and videos would add a strong element of visual interest to the material. In the short-term, spending more time discussing application of the principles to senior design projects than to future work in industry would both increase efficiency in senior design groups and engage students more directly with immediately relevant material. Overall, response to the lecture was very positive; one student commented that "I actually learned a lot, probably the best lecture of the semester for me."

Discussion

After reviewing and comparing the results from the two surveys, it was evident that there was significant improvement in the student's' knowledge of lean manufacturing from the lecture, discussions, and group activities. Students correctly answered the survey questions at a higher rate and were able to apply the concepts learned to their projects.

An unexpected result from the survey was the popularity of answers focused on the philosophy and management implications of lean environments. This was surprising because, though it was explained in lecture, the psychosocial aspects of lean manufacturing were not significantly emphasized as a learning objective. This agrees with the findings of Jeffrey Liker in "The Toyota Way" - many companies that try to implement lean thinking do not achieve the full benefits of a lean production environment because they do not incorporate a lean culture in the workplace designed to engage all employees (Liker, 2004). Many students mentioned that "Not Utilizing Talent" was a major waste their teams experienced, and they suggested many ways that they could better utilize team members' individual skillsets. The first was clearly identifying team members' strengths and weaknesses at the beginning of the project, allowing for teams to assign tasks to people with a particular skillset, or to have multiple people focus on unfamiliar material. Additionally, getting input from all team members in meetings is important to maximizing outputs. Having a multiplicity of opinions allows the team to build upon each; establishing methods that allow for all team members to give their input on various challenges can increase problem-solving ability dramatically. Having "fresh eyes on the subject" allows for new and different opinions, providing the opportunity for students with different backgrounds and experiences to give their unique approach to solving the problem. This synergistic approach to problem-solving aligns with the ideas presented in lean culture.

These findings illustrate that when teaching lean manufacturing, it is imperative to emphasize not only the process, tools, and techniques, but also the psychology of management ideas addressing the continuous pursuit of perfection and team-centered ideology. To truly implement lean in an educational engineering project, the process must begin with proper management and organizational structure both within teams and from class instructors. This includes having a well-defined mission statement and a definition of value according to the customer, whether that be an industrial sponsor, competition judges, or faculty at a university. Having better management techniques in place, and defining value early in the project lifecycle, will improve final quality, improve team communication, and facilitate better knowledge transfer between team members. A better management style would allow more autonomy for students and reduce the amount of wasted time they experience waiting for directions from sponsors, advisors, and other team members. These results agree with findings in other studies on perceptions of lean implementation in university settings (Jahan & Doggett, 2015). Additionally, by giving team's official training on teamwork and team building, student groups could create a much more efficient project culture. This would allow them to implement the lean focus of *kaizen*, implementing continuous improvement to allow their groups to operate more efficiently, streamlining the application of a group's knowledge to a project.

Building official training on lean cultural principles into the curriculum would render significant improvements to senior design teams efficiency, not only strengthening their ability to solve problems, but also removing many of the inefficient wastes they suffer throughout the process. Two of the most frequent problems identified by senior design groups were waiting on guidance and failing to utilize team members' talents effectively. Implementing lean changes to the organizational structure of senior design groups, both internally and in communication with advisors and sponsors, would significantly reduce the waste created by these problems. Prioritizing knowledge transfer within teams, and between teams and faculty, will not only produce greater team synergy; it will also enhance the productivity of students on an individual basis. Beyond the technical advantages of implementing lean cultural practices, there are also positive considerations to be explored in terms of networking and building relationships, anticipating the entrance of graduating seniors into the workforce.

In the spirit of *kaizen*, there are a number of improvements that can be implemented in the short-term to begin building a lean culture in the mechanical engineering senior design program as well as in preparation for future senior classes and in preparing a lecture for next year. Based on the results of the surveys given to students on lean manufacturing, a number of relatively small changes could be made to begin, gradually and continuously accumulating into greater and greater improvements in educational outcomes. Increasing the amount of student engagement by expanding the use of I-clickers would help create positive feedback loops between instructors and their students, identifying and correcting areas where further development is required. Implementation of 5S in all senior design projects would represent a substantial improvement in group efficiency, enhancing communication between team members and ensuring that all resources are applied to their fullest potential. Many students felt that communication and management techniques similar to *kanban* notification boards could be better utilized by all teams to better manage procurement as well track project tasks. In the planning stages of senior design groups, the creation of a value-stream map would help teams develop a roadmap for success throughout the life of the project, anticipating needs for material and expertise before they arise and preparing accordingly in advance. The sum of these changes would represent a substantial improvement in student efficiency in line with lean principles, both teaching them the application of these principles for the future and immersing them fully in a truly optimized, lean system.

Conclusions

It is evident that introducing lean manufacturing material into the curriculum would be beneficial to senior design students. Training on the subject enables students to think and operate with a lean mentality, improving the efficiency and quality of senior design projects. Though it would be difficult to incorporate every aspect of lean into all senior design projects, many lean tools, such as 5S, value stream mapping, and *kanban* visual reporting systems could be easily implemented into a majority of projects.

However, it was evident from the student responses that some of the wastes they experienced were due to how the class was organized and managed. Improving this falls on the shoulders of the educators, project advisers, industry sponsors, and various academic departments. Establishing a lean culture in the mechanical engineering department would be the preliminary step in creating a truly lean senior design project. Suggestions for the Mechanical Engineering Department at Colorado State University to better educate students on lean as well as improve the efficiency of the senior design capstone class would be:

- Have advisors, sponsors, and end customers define the “value” objectives of project outcomes prior to students beginning working on the projects.
- Incorporate lean manufacturing training early on in the semester through a series of at least two lectures.
- Require teams to implement 5S in their individual projects and work areas.
- Have students create value stream maps during the project planning stages and continue to update them as they become more familiar with project tasks.
- Have teams develop visual reporting systems and cues in work areas to illustrate project status, upcoming activities, and improve procurement management.
- Include sections for students to document lean implementation and allow for self-reflection and methods to continuously improve in class deliverables including the project plan report, mid-year report, and final report.

By facilitating the teaching of lean manufacturing and methods, educators in engineering universities can better prepare their students for careers in industry. Students would be encouraged to think critically and proactively identify wastes, vital skills for the marketplace. Employers will not have to spend time and money training new graduates in basic lean principles, and the transition to working in a lean corporation will be much smoother, leading to shorter onboarding processes. Even with introductory training on lean manufacturing, CSU engineering students were able to quickly grasp the major concepts of lean and then apply the new knowledge to the processes they undergo on a daily basis in their own design projects. By educating students on the types of waste defined in lean theory, it was easy for them to see that many of these wastes were rampant in their design projects. After identifying these wastes, it was possible for students to develop novel methods of implementing lean practices in their projects to improve the team's productivity. As a result, students were able to both improve their project outcomes and gained valuable hands-on experience applying lean methodology. These skills will be vital once they graduate into the workforce, regardless of what industry they pursue a career in.

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