2009

Lean Six Sigma Principles In Capstone Aeronautical Engineering Technology Courses

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AC 2009-1980: LEAN SIX SIGMA PRINCIPLES IN CAPSTONE AERONAUTICAL ENGINEERING TECHNOLOGY COURSES

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Abstract

The Aeronautical Engineering Technology program has senior level capstone courses that integrate knowledge gained through undergraduate courses. Three of these capstone courses require the students to plan, design, build, test, and implement product or process improvements. Faculty members have designed these courses in the curriculum to focus students on product design and process improvement. The courses use Lean Six Sigma (LSS) methodology and techniques as a structured approach to problem-solving, product design, and process improvement. This combination of design project experience and LSS knowledge is an advantage for graduates seeking careers in aerospace and aviation, as the LSS methodology is widely used across multiple disciplines to achieve dramatic performance improvements. Many aeronautical engineering technology graduates apply for jobs at major aircraft manufacturers. LSS is one of many valuable skills valued to meet the challenge of filling the gap between engineering, manufacturing, and support. In addition to manufacturing liaison and field engineering positions, these graduates may be hired for positions in scheduling, tooling, design, or purchasing. To better prepare students for these careers, three new courses were developed for capstone design where the students learn and use problem-solving methods and techniques that help them understand the design and improvement of products and processes. Specifically, the courses use two major Lean Six Sigma methodologies: DMAIC and DMEDI. DMAIC is a methodology for process or product improvement with five phases: Define, Measure, Analyze, Improve, and Control. DMEDI is a methodology for process or product design with five phases: Define, Measure, Explore, Develop, and Implement. Both of these LSS methodologies emphasize a data-driven approach to improving processes and the products delivered to customers through reducing waste, reducing variability, and improving speed. This paper discusses the relevance of these methodologies and the implementation in the capstone courses.

Introduction

The Aeronautical Engineering Technology (AET) program is one of three programs in Aviation Technology offered at Purdue University. The AET program has a long history of transforming its curriculum to meet the changing challenges of the aviation and aerospace industries. Evolving from successful aviation operations and maintenance technician program, the program changed its curriculum to become an aeronautical engineering technology program. The first AET students graduated in May 2008. Guiding the curriculum redesign was a strategic decision of the faculty that identified ABET Technology Accreditation Commission (ABET TAC) accreditation as a key competitive advantage for its baccalaureate graduates. One part of the ABET TAC requirements is that graduates can apply technical skills and knowledge "to the analysis, development, implementation, or oversight of aeronautical/aerospace systems and processes[1]." Three senior level courses were developed where students conduct product design, process design, and process improvement projects. The focus of these courses is product design, process design and process improvement. The faculty chose to incorporate Lean Six Sigma (LSS) as an underlying structure for the courses primarily due to the structured methodologies and the wide use of LSS in the aerospace industry. This paper introduces Lean Six Sigma, the courses developed, course implementation and examples of projects.

Lean Six Sigma Background

Lean Six Sigma is used in aerospace companies, in addition to many other types of industries and governmental agencies not related to manufacturing[2,3]. Lean Six Sigma is being applied in a variety of processes in business, design, manufacturing, service delivery, laboratory, maintenance, distribution and supply chain. Lean and Six Sigma were developed separately. Lean is sometimes understood to be the Toyota Production System[4] described by Taiichi Ohno[5]. When introducing Japanese lean philosophy and techniques to the United States, Womack and Jones described a lean philosophy that focuses on customer value and extends beyond the elimination of waste[6]. In 1993, the Lean Aircraft Initiative (now renamed Lean Advancement Initiative) at the Massachusetts Institute of Technology began to formalize and study the effects of lean throughout the aerospace industry and have numerous publications[7]. Six Sigma was developed at Motorola to provide a structured approach to reduce variation in product output in the 1990s[8], and used extensively at General Electric and other aerospace companies. At first, these two methodologies for dramatic improvement were seen as competitors, but in the late 1990s, a Lean Six Sigma approach was developed that combined the strengths of each[9]. The Lean Six Sigma approach combines the data-driven tollgate project methodology and variation reduction focus of Six Sigma with the reduction of cycle time and waste by using lean principles and techniques[9].

Examples of LSS use in aerospace abound. One example of the use of LSS is the improvement of maintenance processes for the M1 Abrams tank US Army[10]. The Corpus Christi Army Depot used LSS on maintenance of the H-60 Pave Hawk helicopter to improve on-time delivery from 8% to 90% while decreasing turnaround time by 45%, labor hours by 47%, and cost overruns by 73%[11]. In 1999, Lockheed Martin adopted Lean Six Sigma adopted as a management philosophy, and since then the idea of process improvement has migrated to every business function such as finance, operations, and cash management, in addition to operations functions[12]. Boeing used LSS to address a problem with re-circulating air fans were rejected during testing on the B777 production line[13]. Replacement was costly and required additional testing. In this particular case, the inter-departmental team found the root cause to be items designed to prevent debris in the first place, such as ductwork caps and plastic sheeting, became debris themselves. The process was changed and the problem was solved[13].

Implementation in AET Capstone Courses

In the Aeronautical Engineering Technology (AET) curriculum, there are courses in design and analysis of systems, but there are no courses dedicated solely to lean and/or Six Sigma. In fall 2007, three new senior level courses were developed as capstone experiences where students participate in team projects that require the students to use skills and knowledge acquired throughout their education to complete a design project. The faculty members designing and instructing the newly added AT496 Applied Research Proposal, AT497 Applied Research Project, and AT408 Advanced Manufacturing Processes courses each chose to incorporate Lean

Six Sigma methodologies as a structured approach to process design and improvement, and to product design and improvement.

In industry, Lean Six Sigma is implemented through projects that are selected based on relevance to key business issues and the potential financial impact on the company[8]. The projects address problems that need to be solved to improve the bottom line of an organization. In the three capstone courses, the projects simulate problems similar to those found in industry. To fit within the semester, the projects are scoped such that they can be completed in approximately three months, have measurable impact, are of an appropriate level of difficulty to incorporate skills and knowledge from previous courses, and are interesting to both the student team and the affected process owner. Each Lean Six Sigma project is divided into five phases, with each phase requiring specific objectives and a review, sometimes referred to as a tollgate review. The tollgate review may result in one of three outcomes: continue to next phase, stop project, or continue study in current phase. Within each phase, data is collected and analyzed statistically to aid decision-making. For process improvement projects, these five phases are: define, measure, analyze, improve, and control (DMAIC). For projects that design new products, components, or processes, the phases of the methodology are slightly different: define, measure, explore, develop, and implement (DMEDI). Both methodologies use specialized tools for designing or improving manufactured products[9] and services[2].

The students divide themselves into project teams of three or four students per team. Larger teams create a situation where it becomes more difficult to evaluate the contribution of each student. In AT408, the teams use DMEDI to address problems given to them by the instructor and students select their team members. In AT496, the teams research candidate problems and find faculty sponsors for the projects that may require either DMAIC or DMEDI. The students form their own teams and realize that the teams must stay in place for both semesters to complete AT496 and AT497. (See Figure 1.) A significant portion of a student's grade depends on peer evaluation which is conducted two to four times a semester. There is a consensus among faculty members teaching the senior level courses that the best way to handle those peer reviews is to have a single form for this purpose across most, if not all, senior level courses[14].

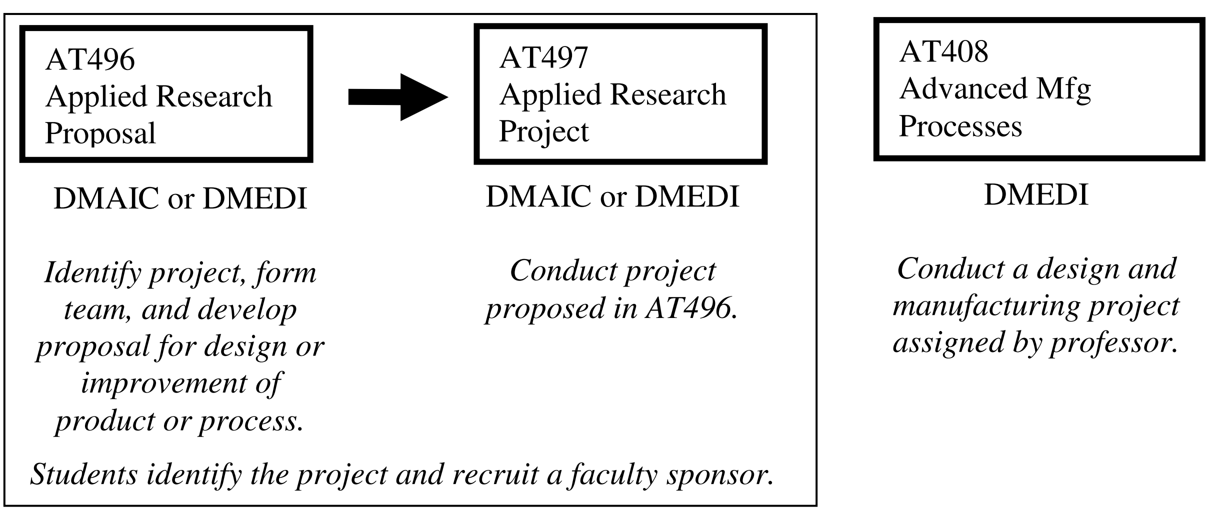

Figure 1: Three Aeronautical Engineering Technology Courses with Lean Six Sigma

The AT496 and AT497 courses were developed in fall 2007 and focused on process improvement projects. The DMAIC methodology was selected because of the nature of the projects and the DMAIC methodology is used in many aerospace companies as a preferred method for process improvement. These two courses are a two-semester proposal and project implementation pair. The AT496 course the student teams prepare proposals that define the problem and measure the baseline. During the AT497 course, the student teams analyze and improve the performance of processes, then develop and implement controls to sustain the gains in process performance. It is very important to note that the AT 496 and AT497 courses are not courses in DMAIC, lean, or Six Sigma. These two courses are project proposal and project implementation courses, with those two objectives being the primary objectives. The DMAIC methodology is being used as a vehicle to proceed through the proposal, implementation, and hand-off stages in the project. The DMAIC methodology helps students tackle a process improvement project in a structured manner. The first year these two courses were offered was 2007–2008[15]. In 2008-2009, the student teams selected either DMAIC or DMEDI in AT496, depending on the type of project the team proposed to complete in AT497.

In fall 2007, the AT408 course was developed to focus on new product design. The DMEDI methodology was selected because of the nature of the projects. The DMEDI methodology is specifically indicated for projects that create a new product, service, or process[16]. DMEDI shares the same first two steps with DMAIC, with the first two phases being define business opportunities and measure inputs and outcomes. The next three phases are different in DMEDI: explore options; develop new product, process, or service; and implement the best solution. The AT408 course gives students an opportunity to go through all five phases of the DMEDI methodology as a vehicle to structure the course while the students learn about new product creation, design, and advanced manufacturing processes.

DMAIC Implementation

AT496 and AT497 are two new senior level courses added in the 2007-2008 academic year. In the fall semester, the AT496 students identify and propose a project for completion during the spring semester AT497 course. First, students are exposed to the DMAIC methodology and then students find a problem that interests them. To find problems, the instructor asks the students to brainstorm in class, and to talk with other faculty members. During the brainstorming session, students are asked to think about activities they had done in labs that could have been done more efficiently. In both fall 2007 and 2208, the students quickly focused on problems that involved taking too much time to do a task because tools were difficult to locate or too far away, or were inconvenient due to the fixtures. The instructor asks the students to sort the projects in terms of high or low difficulty, and high or low impact. The students then form teams and prepare a proposal for the faculty. To successfully propose the project, the team must solicit both cooperation and advice from the persons responsible for the operation of their target process. These process owners are typically one or more faculty members who oversee other AT laboratories. For instance, the students may want to propose and complete a project in a laboratory that is not the AT496/AT497 course instructor's lab, but in another instructor's lab such as the advanced manufacturing lab, composites lab, or turbine engine lab. The team members learn new skills in problem-solving such as project selection, team dynamics, and presentations, in addition to learning how to prepare a proposal. After the project is proposed and accepted, the team implements the project in the spring semester. In the AT497 course, the team must use technical knowledge, project management, and conflict resolution skills to successfully complete the project. Throughout the AT496/AT497 courses, the student teams meet regularly with the course instructor and the supporting faculty members in charge of the targeted laboratories. In these meetings, the student teams review progress, ask questions, and are mentored by the faculty.

In fall 2007, all six projects proposed by the students concerned redesigning processes within the laboratories in the aviation technology (AT) department. For example, "perform 100-hour power plant inspection," "control magneto testing equipment inventory," and "stage and de-stage turbine engine," were three of the six processes identified for redesign by student teams[14]. In fall 2008, the seven projects proposed by students were divided between DMAIC and DMEDI projects. In the proposal, the teams were required to identify the problem, its significance, a goal that addresses the problem, and a plan to address the goal. During the development of the proposals, the student teams were instructed not to focus on the solution, but rather to focus on identifying the problem, defining the problem in terms of performance parameters and the "as-is" performance levels, identifying the goal or "to-be" level of these parameters, and developing a plan to achieve the "to-be." In both years, all of the projects were in laboratory areas not controlled by the AT496/AT497 instructor. The teams had to acquire cooperation from other faculty members who controlled those laboratories. The AT department assisted this process by offering a faculty workload release.

In the second semester, the teams each revised their project plans and used Gantt charts to self-manage the projects. In a manner similar to a Master Black Belt[2,9] or a program manager, the instructor's role was facilitator, mentor, and technical instruction and guidance on the use of tools. The student teams scheduled their time and meetings with professors; monitored their performance; provided weekly Gantt chart updates; and presented impromptu short updates in class. Figure 2 contains a one-page weekly project update report format with an example Gantt chart. The weekly report lists in bullet form the accomplishments of the previous week, the specific plans for the upcoming week, the issues facing the team, and a summary of the hours spent on the project for each team member. The first few times a team produces the weekly report presents challenges to the teams as this is their introduction to Gantt charts and weekly reports. After two or three weeks of practice producing the charts and incorporating constructive feedback, the student teams produce the charts within ten to fifteen minutes. More importantly, the teams begin to use the charts to plan and manage their projects. The Gantt chart presented in Figure 2 is a high-level chart prepared early in the project by a student team. The gap in the calendar reflects the team's realistic view that no work would be accomplished during the winter break. Each team developed a more detailed chart early in AT497 that expanded the more detailed tasks within the project phases. In class, the student team updates focused on the challenges being faced, ways to overcome the challenges, and discussing alternative solutions or approaches with classmates.

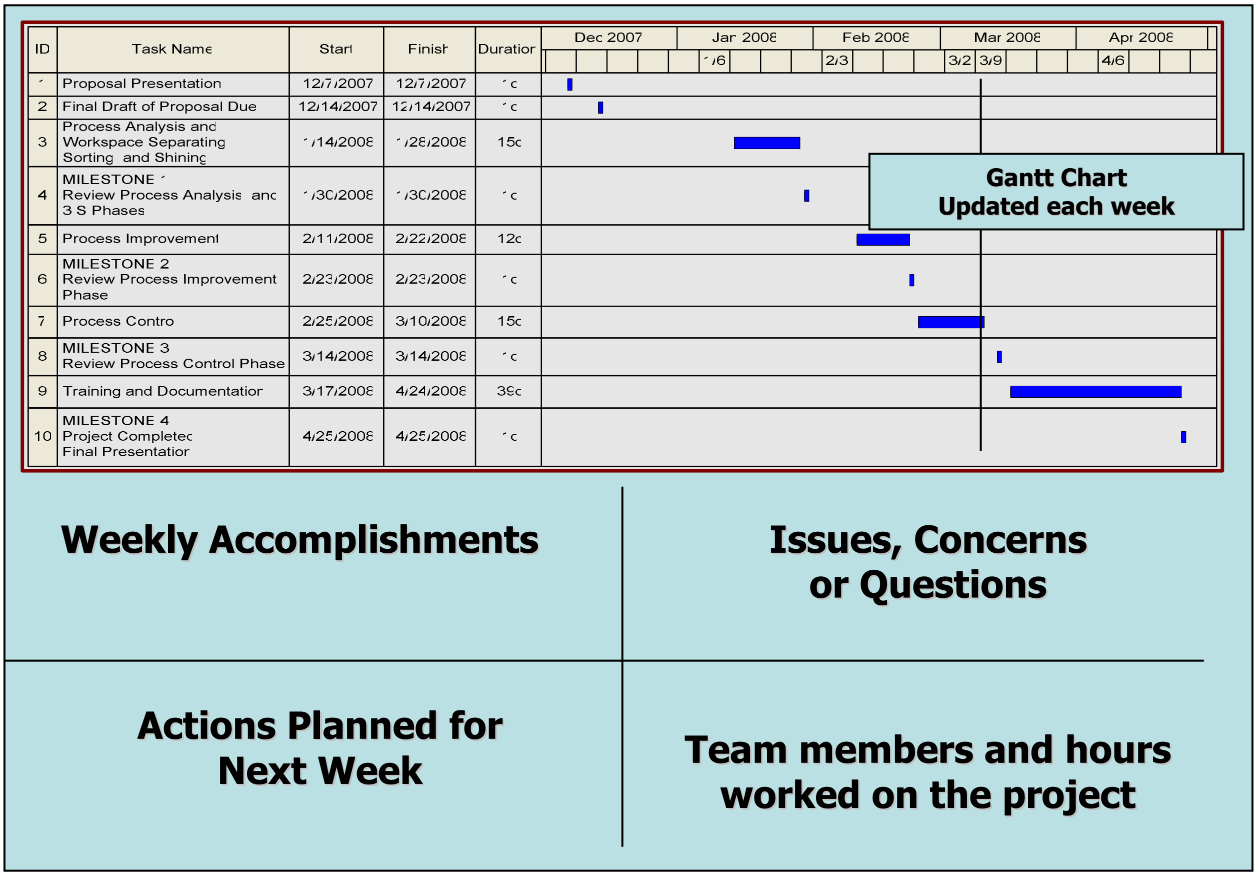

Figure 2: One-Page Weekly Project Update Report Example Format

As an added difficulty for these projects, the team members not only had to agree among themselves but also had to convince the faculty of the affected laboratory that the project was worthwhile, that the solutions were appropriate, that the control methods implemented would contribute to sustaining the gains in performance, and that the quantified benefits were realistic. To accomplish this, the teams scheduled meetings with the faculty sponsors to review the project. Depending on the nature of the project, the teams selected and used Lean Six Sigma tools[2,8,9,17], such as 5S, process mapping, SIPOC, experiment design, work sampling, data collection and analysis, spaghetti diagrams, statistical tests of significance and hypothesis testing, failure modes and effects analysis, pareto charts, and voice of the customer to reduce the number of process steps, reduce cycle time, and improve accuracy or safety. The students take a statistics course prior to AT496. In AT497, the instructor introduces a statistical software package (Minitab© from Minitab, Inc.) to facilitate the students' use of statistical tests, graphical analyses, and other statistical analyses.

At the end of the semester, each project team prepared both a written report and a presentation. The audience for the team presentations included class members, the course instructor, and other faculty members. In addition, one student team presented their project to the AT program industrial advisory board meeting held in April 2008. The aerospace industry board members viewed the other projects during a tour of the laboratories. The board members agreed that the projects were the types of project experiences valued in newly hired graduates of aviation technology.

DMEDI Implementation

The AT408 Advanced Manufacturing Processes course was developed and implemented in fall 2007. The course exposes students to both "worlds": the hands-on world of manufacturing and the other world of component design processes. The course introduces the students to the design process, and requires them to create working instructions, process sheets, and drawings, then manufacture components, assemble them, and perform testing and final adjustments. Prerequisite coursework prepares the students for the challenges of AT408. Up to this point the students have learned in the curriculum how to follow instructions, document their progress, and how to work in teams assigned by a course instructor. In AT408 the students receive full freedom to plan their projects, establish necessary steps and deadlines, and carry out a project. The students must even select their teammates. Many students find it hard to handle because of this higher level of freedom received for the first time in the curriculum. After deadlines are set, the students are held responsible by the instructor to meet those dates. Students become active participants in their learning process[18].

In AT408, the students are required to use the DMEDI methodology to create a product starting with a defined need and ending with a physical assembly. Because of a short duration of the course, one semester, the course instructor begins the DMEDI process for the student teams by completing the define phase. This gives an opportunity to introduce undergraduate students to the research needs of the whole department. The student teams then complete the other four DMEDI phases with guidance and mentoring from the instructor. It is possible to use other faculty members as mentors for this purpose. In the first offering of the course, the students were given a task to design and produce specific missing components for a Pratt Whitney PW4000 turbine engine in the AET Turbine Laboratory such as turbine vane and blade cooling air shutoff valve, variable stator vane actuator control system (see Figure 3), fuel flow transducer, etc. In that current state, the engine could not be used as a visual aid, which means it could not serve an intended purpose. The engine needs system components to be designed, manufactured, and installed to serve as a better visual aid in other AT courses.

The AT408 course projects are not limited to just design of mockup parts and assemblies. In the fall 2008 AT408 offering, one of the teams designed and manufactured a storage rack for the engine cowlings removed from the Boeing 737 used in another AT course focused on aviation maintenance. The team designed the rack to hold the cowlings to facilitate more hands-on training with the B-737 engines. Another project with practical application was the design, fabrication and assembly of a mobile rocket launch platform created with collaboration with Purdue University Rocket Propulsion Laboratory.

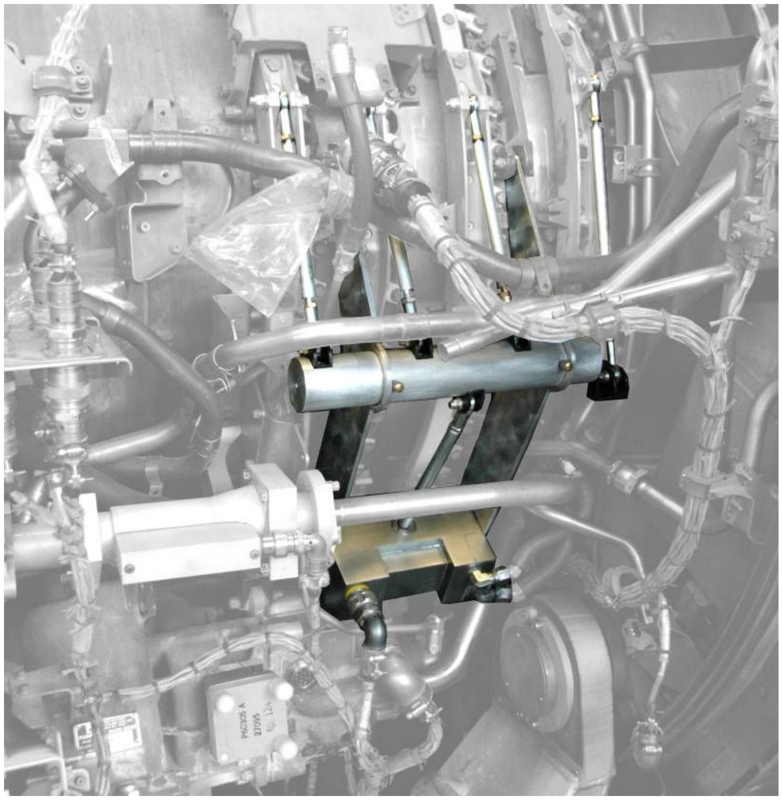

Figure 3: Variable stator vane actuator control system project

In the AT408 course, students work in teams and learn to communicate effectively with each other, with a customer, and with upper management. The students learn problem-solving skills and tools, such as brainstorming, 6-3-5 method, and Decision (Pugh) Matrix. The major milestones of the course are the conceptual design review (CDR), detailed design review (DDR), and final presentation[19]. All three reviews are oral presentations in which each team discussed their findings and progress. The most difficult part of a project is to generate at least three unique design concepts of a device to fulfill customer's needs. Brainstorming, one of many Lean Six Sigma tools, is used for this purpose. Another challenge is to select the best concept using a Decision (Pugh) Matrix, which is another tool used in DMEDI methodology.

The students use the decision matrix to establish a datum concept and set of weighted criteria, and then compare two alternative concepts according to selected criteria (see Figure 4.) In this case, evaluation of the concepts becomes more objective. The best concept has the highest score[8].

Criteria	Weight (1-5)	Concepts					
		Concept 1		Concept 2		Concept 3	
		Rating (-3 to +3)	Score	Rating (-3 to +3)	Score	Rating (-3 to +3)	Score
Criteria 1	5	Datum		1	5	3	15
Criteria 2	3			-3	-9	2	6
Criteria 3	4			0	0	-1	-4
Criteria 4	3			-2	-6	0	0
Criteria 5	2			1	2	-1	-2
Criteria 6	3			-3	-9	-3	-9
Criteria 7	2			-2	-4	-2	-4
Criteria 8	1			0	0	0	0
Total =		0		-21		2	

Score = Weight * Rating

Figure 4: Example of Decision (Pugh) Matrix

Conclusions and Future Work

The Aeronautical Engineering Technology program has developed capstone experiences in design and improvement of processes and products. Two Lean Six Sigma methodologies are used as vehicles for the students to proceed through their projects. The three AT courses are project based. The students learn by going through the phases of design creation or process improvement. The instructors of these courses collaborate on the use of methodologies and tools, as well as sharing experiences to improve the outcomes of the courses. In addition, the instructors are collaborating with the instructors of prerequisite courses to incorporate process mapping, statics, problem identification, and Gantt charts at earlier points in the curriculum. With more common elements in upper level courses, there is a greater opportunity for student understanding with repeated use. Introducing and using common elements earlier would allow more time for in-depth questions for instructors.

The work on common course elements has begun, but there is still more to do. Initial steps to create and use a common team evaluation form took place in spring 2008. A common team evaluation form was developed and used in upper-level courses[14]. The instructors are also working together to establish common guidelines for writing a proposal, creating presentations, and reporting content. A difficult part that remains is to design a common set of rubrics for project evaluation and student learning outcomes that could be applied throughout the senior level courses and adapted for lower level courses.

In the future, it might be possible to ask the AT408 students to come up with their own ideas for an interesting product. The biggest obstacle to starting the process with the students generating an idea is the limited amount of time available in the one semester allocated for the course. The students in the projects establish deadlines, design the parts, and produce 3D computer aided design models, drawings, process sheets, and a cost analysis. In addition, the students manufacture the parts in the materials and manufacturing laboratory and build the final assembly. The ultimate goal is use undergraduate student teams to work on real-life project for industry, both nationally and internationally.

The work accomplished this far has provided a solid foundation for future course improvements and has demonstrated the use of Lean Six Sigma methodologies. To strengthen the courses, the instructors are planning to incorporate more project based learning techniques beyond the instructor acting as a facilitator and the development of problem solving skills in a team environment. Similar to Beringer's findings[20] in problem based learning, the instructors in the AT496, AT497, and AT408 courses observed that the projects were not structured sufficiently for some students who only focused on the technical aspects and not the entire collaborative design experience. In addition, the instructors are meeting informally with the instructors of the lower-level courses to incorporate introductions of specific tools into these earlier courses.

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