AC 2007-268: EMPLOYING LEAN ENGINEERING PRINCIPLES AS A STUDENT EXERCISE TO MODIFY THE CONTENT OF TRADITIONAL AIRCRAFT AND PROPULSION DESIGN COURSES

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Employing Lean Engineering Principles as a Student Exercise to Modify the Content of Traditional Aircraft and Propulsion Design Courses

Lean manufacturing, lean engineering, and application of lean thinking throughout an entire enterprise are issues which appear to comprise one of the waves of the future in the aerospace industry. The MIT-managed Lean Aerospace Initiative (LAI) has made specific steps over the last three years, several of which have involved ASEE, to bring more educational institutions into the lean thinking pool. It has established the LAI Educational Network (EdNet) to encourage universities to incorporate lean principles into their curricula. While a separate course of the systems engineering style is the obvious way to accomplish this goal, it is possible to introduce a brief but meaningful lean engineering experience into an existing design course without totally disrupting the traditional flow of course material. This paper describes four recent experiments which have proven to be successful within a traditional Aircraft Preliminary Design course, as well as a different approach to implementation of lean principles in a Propulsion Design course.

The Aircraft Preliminary Design course

Within the Aerospace Engineering degree program at Embry-Riddle Aeronautical University there is a two-semester capstone sequence of aircraft design courses which has a long history of being well regarded by both students and employers. The first author is currently teaching the first of these two courses, Aircraft Preliminary Design, AE420. In this course a booklet of handouts describes the overall course format and the 16 deliverable tasks. This 30-page document has evolved over the 28 years that the author has taught this course and serves as a reasonable representation of the traditional aircraft design process, or “current state” process.

In more detail so that process diagrams are understandable to readers of this paper, the current state is defined by a Statement of Work which defines project requirements, design specifications for the semester, grading criteria, deliverables required (six design review written reports, two oral presentations, five quizzes, and peer evaluation of each individual’s productive participation in the project), report format and drawing format. The SOW is supplemented by 16 Word documents, each of which defines a deliverable task in greater detail. The 16 tasks are:

- Task 1 – Conceptual design, by each individual student
- Task 2 – Oral presentation of individual conceptual designs
- Task 3 – Second iteration of the conceptual design selected by each design team
- Task 4 – Wing design
- Task 5 – Fuselage layout
- Task 6 – Engine installation and propeller noise
- Task 7 – Landing gear layout
- Task 8 – Structural concept
- Task 9 – Weight and balance
- Task 10 – Stability and control
- Task 11 – Inboard profile drawing
- Task 12 – Drag and performance
- Task 13 – Cost analysis
- Task 14 – General arrangement drawing
Task 15 – Computer Aided Manufacturing (CAM) of team’s design
Task 16 – Final report
A day-by-day schedule for the entire semester with due dates for each task is also provided.

To introduce Lean Engineering, two hour-long presentations were developed. Both of these were adaptations of the copyrighted modules of the MIT Lean Academy, for which the author is an instructor and which are available to EdNet members. The first module is an overview of the history of the aerospace industry and why the need for lean thinking evolved, titled “Aerospace At 100 Years”. The second is specifically “Lean Engineering”, a primer on how lean engineering analysis is done. Both of these modules were abbreviated significantly, from 32 and 60 slides to 13 and 29, respectively. And the discussion was curved toward the content of this specific course as well as the prerequisite knowledge of this particular group of students.

The assignment given to each student team was to first prepare a process flow diagram and value stream map for the “current state” traditional design course. The process flow diagram, Figure 1, is a fairly intuitive graphical depiction of the flow of effort and information through the design

![Original Process Flow Diagram](image)

**Figure 1. Example of student-generated process flow diagram for a MAV**
course. Then, based on the color coded value-added versus non-value-added judgments in the current process flow diagram, a revised course content proposal was created by attempting to eliminate or minimize waste. From this revised course content, each team generated a revised “desired state” process flow diagram and value stream map. The decisions about value added or not were made during group discussions within the design team, based upon their collective experience and intuition, and were generally substantiated and logical. Each of the teams presented to the rest of the class a Power Point review of its lean engineering process and its conclusions, from which Figures 1 and 2 are taken. The consistent recommendations were then used by the instructor to modify the course schedule and the list of deliverables for that semester.

The outcomes were fairly predictable and were heavily influenced by the nature of the design specification for that semester. In the first trial in Fall 2005, one section that exercised this process included 28 students in 4 teams designing a Micro Air Vehicle (MAV), a remotely controlled aircraft with no dimension greater than 6 inches. Since the vehicle is hand launched, clearly the landing gear layout in Task 7 is unnecessary waste as is the quiz covering that material. And the team which created Figure 1 also felt that the MAV definition was sufficiently restrictive that the usual conceptual design procedure in Task 1 would need to be significantly modified, which they indicated by their own idea of color coding it blue. It seems that they also felt that Task 1 would be modified in such a significant way that the oral presentation of the conceptual design, Task 2, would be rendered unnecessary waste. They also indicate by blue color that they feel modifications would need to be made to fuselage layout, engine installation, performance, and cost analysis, all of which seem consistent with designing a small radio-controlled vehicle relative to a typical general aviation manned vehicle. After considering all four teams’ suggestions, the implemented modification of course content added a totally new...
task for selection of the components of an electric system to include motor, flight control, and visual navigation instrumentation. And instead of the usual display-only CAM models, each team was required to show a video tape of their vehicle in flight, an interesting and challenging activity in itself.

The other course section for Fall 2005 was 21 students in 4 teams designing a light jet. As expected, there was no significant recommended change in traditional content for this traditional project specification. There were a few recommendations for modifying the timing of some tasks to keep the value stream map flowing more productively but as described in more detail later, these recommendations were based on an incorrect assumption of the serial versus parallel nature of the task work and were not implemented.

In Spring 2006, 3 larger teams formed from a total of 26 students applied the lean analysis process to a 4-seat, propeller driven, short takeoff aircraft. Though this is a traditional type of class project, there were unusual limitations based on the desires of the corporation which requested the project. The aircraft was already designed almost to completion and the student teams were asked to revisit the existing design to see if they agreed that it was properly done. As a result, the lean engineering presentations suggested that it was unnecessary waste to repeat the conceptual design, wing geometry design, fuselage layout, engine installation, landing gear layout, and inboard profile drawings. The students had been told specifically that placement of the 4 seats was not finalized and therefore that weight and balance calculations were not complete, which makes the fuselage layout and landing gear placement clearly not unnecessary waste. It must be that most students have too limited a mental image of the breadth of the influence of design changes. The other suggestions were implemented and the schedule adjusted accordingly.

In the Fall 2006 semester, 50 students in 8 teams analyzed the design process as applied to a modern, high performance, 4-seat, general aviation aircraft. Again this project came at the request of a corporate entity, who this time had a desire to see a specific engine used for marketing reasons. Obviously this puts the engine installation task into the limited productivity category but leaves most of the traditional design process intact, which most teams recognized and recommended.

In Spring 2007, which is just getting started as of the deadline for this paper, 36 students in 6 teams will analyze a more unusual concept dubbed PAV (Personal Air Vehicle) by the NASA Centennial Challenge program. This program specifically targets innovation in design such as use of alternative fuels, noise reduction, ease of operation and navigation, all weather capability, and safety. It focuses on a 200 MPH vehicle that is so easy to operate that anyone who has a driver’s license can safely operate it on an 800 mile trip in any weather, a fascinating if optimistic idea. It will be interesting to see where the students’ imagination takes them, and their lean engineering analysis will tailor the course content to their selected path.

The introduction of lean engineering has been an instructive experience. The logic behind the lean concept is so clear and compelling that the students adapted to it easily and quickly. The formal lean engineering assignment covered a week and a half of class time, so that it was not necessary to dramatically alter the flow of the existing course. In most cases the lean
engineering analysis simply replaced the individual conceptual design portion of the process, Tasks 1 and 2.

And the modified course content was successfully implemented. In each case tried so far, the nature of the design specification was quite different, so that the changes made in “leaning” the design process were different. But changes were always made. Representative excerpts from the teams’ PowerPoint presentations of their recommended changes were selected as Figures 1 and 2.

It is interesting to note that there were some consistent misinterpretations of process flow and value added. These were primarily related to the difference between an educational enterprise and a commercial product enterprise. Even though student teams were required to list and discuss stakeholders in the design process, persons or organizations whose needs define what characteristics are valuable in the end product, the students’ actual assignment of value to steps in the process often ignored those stakeholders. For example, teams often recommended dropping quizzes and even design reviews from the course deliverables because they did not “make the product more valuable”, even though they had just stated that the instructor and the university are stakeholders in this educational engineering process and need data to document the grades given. Another almost universal process flow diagram phenomenon is that people who have never experienced participation in a design project seldom recognize that many tasks must occur simultaneously in parallel processes. They usually diagram the design process as a single path, serial process, and even comment fairly often that a parallel process would be faster and more efficient.

And the lean thinking mindset has germinated in the instructor’s mind some changes to the handout “traditional design process” that will probably be made in the immediate future. Formal, written design review reports will probably be replaced, except for the final report, by verbal, in-class status reports. This will reduce the time burden on both instructor and students significantly with, I hope, little effect on the final product quality. I am not totally comfortable that it is OK to circumvent the careful error checking which occurs during the grading of written design review reports. Also, several of the tasks include drawings of portions of the design as it progresses. And the creation of traditional drawings, even on a good CAD system, seems to be more of a distraction than it is worth. Those traditional drawings will probably be replaced (already have been, to a large extent) by tracking the evolution of a single Catia solid model. And formal discussions have already begun with other degree programs on the practicality of coming up with interdisciplinary capstone design projects that involve several departments. This is a logistics challenge of some magnitude, but seems to be the real world trend that employers want education processes to attempt to replicate.

The Propulsion Design course

A somewhat different approach was employed by the second author for students in the Propulsion track of the same degree program. The propulsion design class is the capstone course for students and enrolled in the propulsion track. Principles of Lean Engineering were introduced and the students were tasked with trying to re-engineer a part, a component, or the entire turbofan engine with a new value statement as the backdrop, with their goal being to
eliminate waste and increase enterprise value while delivering a product that is highly synergized.

Over the course of last two semesters the initiatives were centered on the reduction of number of parts, with two ideas emerging as particularly interesting. The first class of students decided to introduce the concept of modularizing the compressor component of the typical turbofan engine. This allows for increased number of common parts among engines of differing sizes and duty cycles. A student member of that team decided to stay on for graduate school and pursue modular compressors further. The second class pursued the idea of a versatile core. That is, to design the core of the turbofan to be able to handle fan blades of differing sizes and modify only the low pressure turbine component in order to supply sufficient power to run the “new” fan.

More specifically, the principles of Lean thinking were introduced to the students and the discussion quickly shifted to the role of the design engineer in helping the enterprise maximize its stakeholder value. Recent studies have shown that roughly 80% of the Life Cycle Cost (LCC) of a typical product is permanently embedded in the product’s “DNA” by engineering. It is therefore incumbent upon the design engineer to consider the impact of his/her design on the other members of the organization such as manufacturing and service.

An important area where the design engineer can contribute to a Lean organization is part count. Reducing part count, as well as reducing variability in complex parts, can lead to several benefits. These benefits include a reduction in R&D expenses and time, a reduction in tooling and associated costs, a reduction in the number of possible mistakes on the shop floor, as well as an overall reduction in the component cost due to volume purchasing.

The compressor component was then quickly identified as a possible candidate for part count reduction. It was chosen due to its overall complexity, time necessary for assembly and service, expensive materials, and overall number of parts. A modular compressor concept was introduced and a preliminary design [on a conceptual level] was conducted to show the possible benefits of such a concept.

Background and Literature Survey for the Modular Compressor project

The original gas turbine modular concept was first developed in the early 1960’s. Its purpose was to lower the Operating and Support (O&S) elements of the Life Cycle Cost (LCC), specifically, allowing for easier maintenance and parts replacement. This flexibility would decrease engine repair time and effort, and ultimately would minimize maintenance costs. Some examples of the modular engine design are the General Electric CF6-6/50 (Fig. 3) for commercial applications, and the Pratt & Whitney F-100 engine used on the F-15 fighter aircraft.

Duvall, and Goetz outline an understanding for the maintenance procedure with the modular engine concept, with emphasis on the attempts by the military to reduce gas turbine maintenance costs. Lehmann covers the common core concept in detail. The core in Reference 4 refers to the High Pressure Compressor (HPC), main combustion chamber, and High Pressure Turbine (HPT). Furthermore, the benefits of having a common core as they relate to cost savings in terms of development, operation, and maintenance are well outlined. Skira, covered the cost reduction.
efforts that are currently ongoing in commercial, and government institutions. One such effort, receiving much notoriety, is Integrated, High-Performance Turbine Engine Technology, or IHPTET. This is an ongoing collaborative effort by the Air Force, NASA, and various industrial partners. The IHPTET program has some very ambitious goals not only in terms of performance enhancements, but also in terms of cost savings as well.

The HPC casing of the CF6-6 engine, shown in Fig. 4, was removed in order to expose the airfoils and allow the students to better understand this component.

The modular concept aims to achieve the following: the compressor is subdivided into five (5) modules. They are the inlet module (IM) consisting of the inlet ducting and inlet guide vane (IGV), followed by the front module (FM) which includes the front stage but could be extended to include the front two stages. The third is the most important and is the core module (CM). The fourth module is the rear module (RM) and consists of the last stage, and the fifth is the exit module (EM) consisting of the outlet guide vane (OGV) and exit diffuser. Figure 5 shows a schematic of a 10-stage HPC compressor breakdown into 5 modules. In Fig. 5, the FM consists of one stage and so does the RM, while the core module (CM) size is maximized at 8 stages. Both the IM and EM contain each a guide vane and the inlet “swan neck” ducting, and the exit diffuser, respectively.

The intent of the modular concept is to maximize the size of the core module for use in other compressor configurations, for other engines. Pre-planning the different configurations is of utmost importance, and is the key success factor. The core module is then designed with sufficient aerodynamic and mechanical robustness to manage the possible configurations. For example, if a higher mass flow upgrade is planned; the mechanical evaluation of the CM airfoils
must be conducted at the higher mass flow to ensure sufficient stress margin. If a different mechanical speed (rpm) is planned, then the core is evaluated aerodynamically at both speeds (original and modularly upgraded) to ensure stability and conduct sufficient airfoil tuning to handle both operating configurations. Modular upgrades can then focus on the remaining four modules only to be “connected” to the same core.

Figure 6 shows a possible example of a modular upgrade. Fig. 6 (a) depicts a HPC that has been divided into the prescribed 5 modules. This was planned ahead of time by the design engineer in
anticipation of a modular upgrade. Fig. 6 (b) depicts a modular upgrade of the compressor in (a), whereby the core is common, as well as the rear module (RM). In case (b), the design community already has in its possession a working design of 9 stages (namely stages 3-11), thus realizing significant savings in R&D effort and time. Furthermore, manufacturing and purchasing, having already built the compressor in (a), realize substantial savings in lead time, and tooling, to name a few.

Figure 6. Modular upgrade with an 8-stage common core: (a) 10-stage original configuration, (b) 13-stage modular upgrade: higher flow rate, and pressure rise, with a customized OGV/exit diffuser (EM).

In conclusion, the concept of a “Lean” modular axial compressor design has been exercised by students with the framework of their design class. The concept prescribes a division of the compressor into 5 modules, with the intent being to maximize the size of the core module. This module is then designed (and bladed) with sufficient robustness to handle the possible upgrades, and downgrades. Pre-planning this process, in anticipation of the coming upgrades, is the key success factor. Substantial cost savings can be realized by adopting this Lean approach. The savings impact all phases of the LCC including development, procurement, tooling and manufacturing, maintenance, as well as the ability of the organization to offer the customer future upgrades and service contracts at substantial margins.

Conclusion

These projects were admittedly highly compacted time-wise and narrowly focused. In the aircraft design course the application of lean engineering was more broadly exercised in an evaluation of the entire preliminary design process. In the propulsion design course lean principles were used to guide the logic of the design of a specific engine component. In both cases the students
developed a practical sense of what lean thinking means and begin to appreciate that their employers will and must follow the lean path to be successful in modern industry.