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Introduction to Lean Enterprise

Lean Enterprise is a corporate philosophy and culture, having its focus on providing and increasing the value delivered to the customer. It pursues this goal through a continuous process of identifying and eliminating waste and non-value-added activities, improving product flow through the enterprise, and pursuing perfection in the final good or service sold to the customer¹. While Lean Enterprise traces its roots to manufacturing, the principles of Lean can be, and have been successfully, applied to many other industries. Companies adopting Lean as a core institutional value have seen significant gains in productivity and profit.

Lean Manufacturing is based on the Toyota Production System. In post-war Japan, the Toyota Motor Company determined that it would not be able to successfully emulate the mass-production methods being used by U.S. automobile companies. The scales of economy that allowed U.S. companies to dedicate production machinery to a single product simply did not exist in Japan, a market one tenth the size of the U.S. market. Instead, Toyota recognized an opportunity to improve on the inefficiencies created by the mass-production model. Toyota accomplished this by creating a fast, flexible manufacturing system – the Toyota Production System (TPS) – that contains the core elements of Lean Manufacturing². Through the patient, consistent application and development of TPS, Toyota has become the leading automobile maker in the world.

This paper presents the results from a recently-developed laboratory module for the graduate-level course in lean enterprise at Cleveland State University. Student teams repeated a paper-airplane manufacturing exercise on several occasions through a semester, allowing for feedback and process improvement from session to session. This paper presents the lessons learned, from both the students' and the instructor's viewpoint. In addition, the Cleveland State experience is placed in the context of similar laboratory exercises conducted at other universities. Guidelines for initiating similar projects at other institutions will be presented.

Background and Relevant Works

The purpose of a laboratory exercise is to engage students in hands-on learning activities. Previous studies have found that active and collaborative participation in learning enhances students' problem-solving and design skills³, and improves retention of skills and knowledge⁴. The author's own experience as a student supports this philosophy. In particular, his participation in a Lean Manufacturing exercise during his graduate education⁵ inspired him to develop a laboratory exercise when he first taught IME 663, *Lean Enterprise*, at Cleveland State University in the Spring 2007 semester.

Laboratory exercises for teaching Lean Enterprise may be classified according to several dimensions of structure. Some exercises cited in the literature occur as one-time events within the structure of a regular course offering. At the extreme, one single-event exercise having a high level of structure can be completed in a 50-minute time block⁶. At the other extreme, exercises can be repeated over multiple sessions during a term, as exemplified by Blust and Bates⁷, Fang, et al.⁸, Johnson, et al.⁹, and in this paper. Most often in the literature, single-session exercises are crafted for time frames between ninety minutes^{5, 10-12} and one day^{1, 13}. Regardless of the time frame, all authors cited here employ repetition as a tool to highlight the difference between non-Lean production and Lean production. The shorter time frames allow for just two or three rounds to be used as a basis of comparison. For example, the exercise described by Billington⁶ uses three rounds (push, pull with lot size = 3, pull with single-piece flow) to demonstrate to students how Lean can reduce work-in-process (WIP). An advantage for multiple sessions, though, is that it provides the students with time to reflect on the events of a previous exercise and plan for the next. The added time permits a less-structured exercise, as students are able to develop their own methods to implement Lean.

A second dimension of structure for Lean exercises is the level of constraint placed on the exercise. Several exercises in the literature – particularly the shorter exercises – are highly constrained in that students are instructed in what to do, and do not have much opportunity to take the initiative and test their own solutions. Longer exercises allow the instructor to remove constraints to student innovation, usually after an initial round. Room for student initiative is critical if student teams are competing against each other in some fashion. Significantly, the author has found that competition can provide a motivating factor for students to put Lean into practice in the laboratory.

A third structural dimension of Lean exercises are the artifacts used for instruction. Some authors use common office supplies to manufacture paper airplanes⁶, lamp shades¹⁰, or paper cup abstracts¹⁴. These have the advantages of being readily available, easy to work with, and inexpensive. Another group of authors use children's building toys such as Lego blocks or K'NEX^{1, 7, 8, 13, 15}. Such toys have the obvious advantage of simple, tool-less assembly and disassembly, and can accommodate assembly design variations. The author notes a personal preference for K'NEX in this context, as they are less constrained than Legos in how they can connect with one another and can give students another challenge to consider in their implementation of Lean.

Other set of authors employ "unique" artifacts in teaching Lean. NIST has made available a circuit-board manufacturing exercise kit, though its cost is certainly higher than many alternatives¹⁶. Johnson, et al.⁹ have students assemble two models of clocks. Verma¹² uses model ships to simulate Lean implementation for dry-dock overhaul procedures. To engage students in a distance-learning environment, Mehta uses computer simulation to model Lean¹³. Students use Microsoft Paint, email, and virtual classroom software during the exercise. As a graduate student, the author participated in the exercise developed by Lilly, et al., employing single-use cameras in a product design and management context. The cameras have the advantages of being inexpensive to acquire (when used, from a camera store), and having a higher level of complexity than most of the other artifacts discussed here. More importantly, the

cameras represent a real device that must be assembled in the proper fashion to function. Student feedback indicates that work with such an artifact is much more effective for understanding the intricacies of Lean production systems⁵.

Of course, laboratory exercises are not the only method for engaging students in learning Lean Enterprise methods. Industry projects offer students opportunities for learning through hands-on experience that cannot be easily replicated on a university campus. Both Fang, et al.⁸ and Lobaugh¹⁷ report on their students' work with local industries on specific projects. Students in both classes report the industry experience as being beneficial, though both authors cite some difficulties experienced by some teams in the execution of the projects, attributed to lack of interest and poor student leadership. Eastlake and Attia¹⁸ present Lean Enterprise to students in the context of senior design projects, where Lean techniques were applied to the design process itself.

Class Exercise

In the Spring 2007 semester, students enrolled in IME 663, *Lean Enterprise*, were given the goal of manufacturing 108 paper airplanes, in three different models, in a half-hour session. The simulated airplane factory was set up in the Manufacturing Processes Laboratory at Cleveland State University, using several tables and a CNC mill present there. The students were given a deliberately-inefficient manufacturing system, and were to apply Lean Manufacturing tools to be able to meet the defined production goals. Six sessions during the semester allowed students to implement, test, and refine Lean Manufacturing methods. The students' efforts were graded according to three performance metrics – total production, profit, and labor per completed unit. Two of the three student teams were successful in reaching the production goals in the final round; the third team fell just short of reaching the goal.

The objective for the laboratory exercise was for student teams to apply Lean Manufacturing techniques towards the manufacture of paper airplanes. The production goal was to make 108 paper airplanes in a half-hour period – a *takt* time of 16.7 seconds. Three styles of airplanes were manufactured in each session: 60 of model “A”; 30 of “B”, and; 18 of “C” (Figure 1). These designs were selected for aesthetics; none were very good flyers. Four airplanes of any model fit on a single sheet of 8-½”×11” paper. Each airplane followed the same basic manufacturing process:

1. **TRACE.** A three-axis CNC knee mill marked the outlines and fold lines for four airplanes of one type on a sheet of paper taped to the bed. A marker was held in the machine's tool holder.
2. **CUT.** The outline was cut with scissors.
3. **FOLD.** The airplane was folded along the marked lines.
4. **TAPE.** A short length of transparent tape was applied to hold the central fold together.

Each station required one student to perform the operation. In addition, the initial laboratory included a student working in a shipping/receiving department, two material handlers, and a production supervisor.

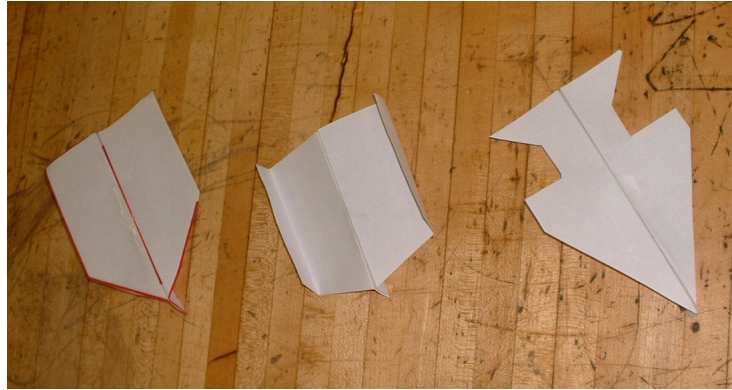


Figure 1. Paper Airplanes, Models “A”, “B”, and “C”.

The initial manufacturing process, layout, and accompanying work rules were designed, intentionally, to be inefficient and slow. In particular, the CNC trace station was the bottleneck operation in the production line. At every station workers were instructed to make as much as possible, as fast as possible, as long as there was raw material available (push manufacturing). Each station also had specialized work instructions, listed in Table 1. Figure 2 shows the initial layout for the laboratory, conducted in the Manufacturing Processes Laboratory at Cleveland State University. The approximate work area shown is 50'×25', and includes equipment not used for the exercise (shaded).

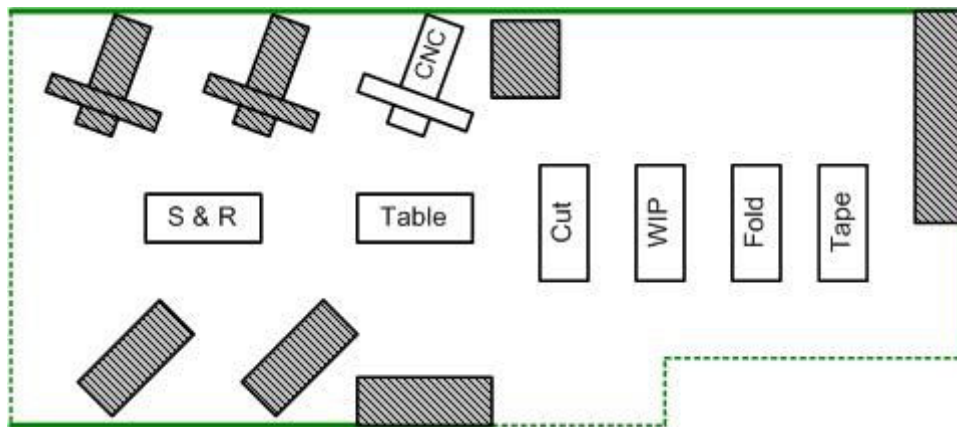


Figure 2. Initial Laboratory Layout.

STATION	WORK RULES
Shipping & receiving	<ul style="list-style-type: none"> • Separate incoming material into stacks of six sheets; paperclip together. • Signal Material Handling (MH) for transport to work-in-progress (WIP) warehouse. • Record time and quantity for completed materials.
Material handling (2 students)	<ul style="list-style-type: none"> • Pick up material from work stations when signaled; deliver to next station if available; deliver to WIP warehouse if next station busy. • Move material only when paper-clipped in the proper lot sizes. Only one bundle may be carried at one time.
Trace	<ul style="list-style-type: none"> • Load proper pen color for order; re-establish pen z-axis zero. • Load CNC program; load paper on CNC bed. • Bundle finished papers six to a stack. Signal MH for transport.
Cut	<ul style="list-style-type: none"> • Cut four airplanes from single sheet of paper. Cut only one sheet at a time. • Bundle 24 airplanes to a stack. Signal MH for transport.
Fold	<ul style="list-style-type: none"> • Fold airplanes 90° along bend lines. Successive bends fold in opposite directions (i.e., up-down-up). • Bundle 24 airplanes to a stack. Signal MH for transport.
Tape	<ul style="list-style-type: none"> • Use approximately 1 inch (25mm) of tape to secure central fold. Place tape in middle of fold. • Bundle 6 airplanes to a stack. Signal MH for transport to Shipping.

Table 1. Initial Work Rules for Paper Airplane Laboratory Participants.

Three merit functions were used in evaluating the performance of students in the lab. The first was total production, measured as the number of correctly manufactured airplanes delivered to the shipping & receiving area during the half-hour session. The second merit function was the labor per unit, measured in man-minutes per airplane. The final merit function was the profitability of the enterprise. Each sheet of paper was assigned a cost of \$4 when accepted by the shipping & receiving area. Each sheet can manufacture 4 airplanes, making this equivalent to a \$1 raw material cost per airplane. The trace, cut, fold, and tape operations each added \$1 to the cost of an airplane, resulting in a \$5 total cost of production. Completed airplanes sold for \$6 each, resulting in a \$1 net profit. Production of WIP and scrap were included in the operational costs. Profit (or loss) and WIP were carried forward from one session to the next.

The class met six times during the semester to perform the laboratory exercise. The first lab session allowed students to become familiar with the manufacturing process, and to see the waste typical in a push production environment. During this first session, the class completed 24 airplanes in an extended 45-minute session. Each airplane required 15.6 man-minutes of labor, and the class incurred a \$416 loss, largely due to the stack of paper sheets waiting at the bottleneck operation. At the conclusion of the first exercise, the instructor conducted a show-of-hands poll to see how many students believed that the class could reach the goal of manufacturing 108 airplanes in a 30-minute session. Not one of the students expressed confidence in their ability to reach this goal.

The second and third rounds were also conducted by the entire class. Prior to these sessions, students developed a list of possible improvements as a homework assignment, and then decided on which changes to actually implement in the following laboratory session. Table 2 shows the gains realized by the class in the first three sessions. The regression in the third round is attributed to an interruption to the production line while a quality problem was addressed. This practice is used in Lean Manufacturing to inform all associates on a production line of quality issues when they arise.

Round	Airplanes Completed	Man-minutes per Airplane	Profit (Loss)
1	24	15.6	(\$416)
2	40	6.0	(\$9)
3	26	8.6	\$38

Table 2. Results of First Three Laboratory Sessions.

At this point, the instructor decided to split the class into three teams. The smaller teams gave students more opportunities to participate in the exercises, as only eight direct participants were needed, at most. In a class of eighteen students, the opportunities for all students to make meaningful contributions to later exercises would have been significantly limited. In addition,

having multiple teams allowed students to evaluate competing solutions to the same problem. As a motivating factor, members of the team scoring the best according to the three metrics were given a “pass” on answering one question on the final examination in the class. Table 3 shows the results for each of the three teams over the three final rounds. Two teams were able to meet their production goals in the last round; the third team just missed the goal.

Team	Airplanes Completed	Man-minutes per Airplane	Profit
<i>Diversity</i>	203 (108 in final round)	2.2	\$112
<i>Innovators</i>	207 (101 in final round)	2.1	\$159*
<i>Lean Machine</i>	211* (108 in final round)	1.2*	\$142

* indicates category leader.

Table 3. Combined Results of Final Three Laboratory Sessions.

All three teams recognized the CNC trace station as the bottleneck process. The G-code supplied to the students traced one paper airplane at a time, resulting in unnecessary motions of the CNC machine. The program for the “A” model, for example, required 59 seconds to trace four airplanes on a sheet of paper. While this time allowed an airplane to be traced in 15 seconds (just under the 16.7-second *takt* time), it left insufficient time for taping paper to and removing the paper from the CNC machine. The loading process also required approximately one minute per sheet, with the CNC idle. To address this issue, all three teams developed methods to multiply the productivity of the CNC station. The *Diversity* and *Innovators* teams replaced the marker with a ball-point pen, and used carbon paper to trace multiple sheets at once. The *Lean Machine* team built a four-pen fixture to be able to trace four airplanes at once (Figure 3). While these methods were made to work, all teams needed some time to develop and refine their changes to the process. Two teams also acted to shorten the loading and unloading times. The *Innovators* designed a pallet system which allowed them to tape paper to the pallet while the CNC was running. *Lean Machine* used a clipboard fixture to eliminate the need for taping much of the paper. The third team did not change the loading and unloading process, but relied on the increase in throughput at the CNC.

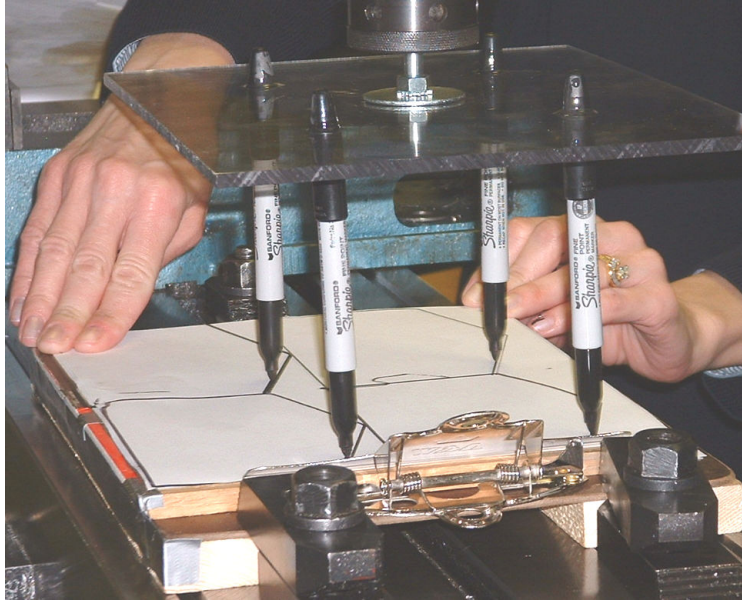


Figure 3. *Lean Machine*'s Four-Marker Fixture.

One team recognized that the CNC trace operation does not provide any intrinsic value to the “A” model of paper airplane; rather, the lines are there to guide the cutting operation. In round 4, the *Lean Machine* team introduced an office paper cutter to cut the “A” model airplanes (Figure 4). Lines marked on the paper cutter guided the operator in aligning the paper properly. This shift to a “low-tech” alternative for “A” airplanes (60 units) meant the CNC was only needed to trace the 30 “B” units and the 18 “C” units. This freed time on the CNC, and permitted the operator to assist in folding airplanes later in the round. It also sped up the cutting operation for the “A” airplanes significantly. As a result, *Lean Machine* was able to lead the labor-per-unit performance metric by a wide margin.



Figure 4. *Lean Machine's* Paper Cutter.

Other “best practices” implemented by students in the IE 606 laboratory include:

- Implementation of single-piece flow and “pull” production through the re-writing of the work rules.
- Physical rearrangement of work stations to minimize travel and encourage single-piece flow. With the exception of the CNC, all of the operations were performed on shop bench tables that were easily repositioned in the space available.
- Elimination of the WIP warehouse.
- Consolidation of the cut, fold, and tape stations.
- Labeling of work areas, using masking tape and duct tape applied to the table surfaces. This was done after one team mixed airplanes still needing tape with complete airplanes, and delivered both to its shipping department.

Despite the success of the laboratory, the instructor noted there was room for improvement in some aspects of the exercise. Foremost, standards for the quality of the delivered product had not been prepared in advance. The instructor inspected airplanes for conformance as they were delivered to the shipping area, but the lack of any quality standards allowed teams to argue that certain airplanes were “good enough”. As an *ad hoc* fix, the instructor accepted marginal aircraft as “seconds” with a selling price of \$3. Between all three teams, a total of 17 airplanes were accepted as seconds, and another 16 were rejected for poor quality. Second, many of the students did not have much, if any, background working with CNC equipment. As a result, the students did not attempt to optimize the CNC code to the extent that the instructor thought they might. The third key area for improving the lab was time management by the students. Teams did not have a specified time limit to set up the equipment for a given session, and some apparently felt no compulsion to test their equipment prior to the lab session. This tended to drag out the exercise sessions and cause the observing teams to lose interest in their classmates’

solutions to the problem. Lacking a motivating factor, students did not take advantage of open lab hours to test equipment outside scheduled lab hours.

Recommendations

Based on the experience at Cleveland State University, the author recommends the following general practices for implementing a Lean Manufacturing laboratory.

- *Initial State.* As with most of the previous works cited, a Lean Enterprise laboratory starts with work rules based on a “push” production system, relying on large inventories, large batch sizes, and infrequent product changeovers. The author recommends designing the process to include a significant bottleneck operation.
- *Open-ended Solutions.* Allowing students to develop their own solutions to the laboratory challenges, rather than following a pre-planned exercise, is immensely rewarding for the students and the instructor. In this exercise, the students shunned solutions considered by the instructor in preparing for the class, and developed solutions that the instructor had not even considered.
- *Repetition.* Repeating the laboratory exercise during the semester works towards two goals. First, it gives the students the opportunity to act on feedback and refine their process improvements. This development process was observed in the Spring 2007 semester, particularly in the *Lean Machine* team’s continued refining of its process. Second, repetition reinforces the concept that Lean is an ongoing process rather than just a one-time event.
- *Time.* Half-hour sessions, including time for set-up and teardown, permit students to evaluate their Lean Manufacturing implementations and observe their classmates, without become too long and drawn out. This time frame allows for multiple teams to demonstrate their processes in a 90-120 minute time block.
- *Goals and Performance Metrics.* Having clear, defined goals and merit functions gives the students objective standards by which to measure their success. The goals should be challenging, but not impossible to meet. The metrics need to be simple to implement and measure; for example, a \$1 standard cost-per-operation used in this exercise. The goal is for students to concentrate on learning Lean through hands-on activities, rather than focusing on accounting.
- *Standards.* Give the students an initial set of standards to guide their work. Have the students modify and refine their written standards before each exercise.
- *Team Size.* Size the teams so that all members can make meaningful contributions. Not all members need to participate in every session, but ensure that all rotate in through the term.
- *Competition.* Having student teams compete, with an award for the “best” team will assist in motivating students.
- *Feedback.* Give the students feedback on their performance beyond the merit functions. Discuss what techniques worked, which ones didn’t, and guide the students in identifying methods to further improve their processes.
- *Pictures.* Use a digital camera to document best practices and other events in the lab.

Future State

Based on the success of the laboratory experience in the Spring 2007 semester, the author applied for and was awarded an internal grant by Cleveland State University's *Center for Teaching Excellence*. This grant will purchase materials to simulate an electronic goods factory in future offerings of IME 663. Instead of paper airplanes, the students will assemble a family of 555-based blinking LED circuits on prototyping breadboards. This artifact was selected for a number of reasons. Unlike the paper airplanes from last year, which did not fly well, the electronic circuits represent functional devices that will require correct assembly to function properly. Use of the solderless breadboards will permit an almost-infinite set of physical configurations that can realize a given circuit diagram. This flexibility gives students room for developing and applying Lean Manufacturing tools in the lab. The breadboards come with row and column locations printed on the boards, facilitating the students' development of standards for component insertion. By not using equipment located in the Manufacturing Processes Laboratory, the exercise becomes portable and may be conducted in virtually any classroom environment. Quality of the finished device will be immediately apparent by observing the operation of the LED's.

The future lab will be administered in a manner similar to that from last year. The exercise will be repeated five times through the semester, reinforcing the concept that Lean is a process and not an event. Each team's session will require 30 minutes – 20 minutes for the exercise, 10 minutes for setup and teardown. In each session, the students will be asked to assemble 240 units – a *takt* time of 5 seconds. The initial work rules will follow those of traditional mass production – large inventories, large batches, and functional segregation within the factory. Students will work in teams to develop competing Lean solutions to the simulated factory, and will be evaluated according to the three performance metrics – profit, total production, and labor per completed unit.

Conclusions

This paper presents results from a recurring laboratory exercise conducted in a graduate-level course in Lean Enterprise. The exercise contains elements that can strengthen appreciation and understanding of Lean Manufacturing, including comprehensive merit functions to evaluate students' solutions, and repetition through the term to reinforce the concept that Lean is a process and not an event. This paper contains recommendations for other instructors based on the experience at Cleveland State University, and at other institutions.

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