Experiences in Simulation-Based Education in Engineering Processes

Hugh McManus and Eric Rebentisch
hmcmanus@metisdesign.com, erebenti@mit.edu

Abstract - The Lean Advancement (formerly Lean Aerospace) Initiative at MIT has applied lean business processes to the Aerospace Industry. The material has proven difficult to teach to engineers, as it is empirical and based on processes founded on human interactions, not scientific and based on mathematical and physical laws. Simulation-based education has proven highly effective in getting past this barrier. Design of a number of pedagogical simulations, and experience with both professional and student audiences are discussed. Data is available to evaluate both a manufacturing simulation and a full simulation of an aerospace enterprise and its supply and engineering chains which capture enterprise interactions. Good data on student satisfaction and perceived outcomes, and lower-quality data on some directly-measured outcomes, support the idea that simulation-based education is highly effective in this challenging situation.

Index Terms – Enterprise, Engineering Process, Game, Lean Engineering, Simulation

INTRODUCTION

Employers of engineering graduates are increasingly concerned not just with the quality of the engineering work done by their employees, but with the processes used in that work. Globalization of the workforce, requirements of customer companies and government agencies, the desire to standardize and certify processes (e.g. attaining ISO certification) and the desire to use lean, six-sigma, and other process improvement techniques all drive this concern for process. This challenges engineering educators to give students at least rudimentary knowledge of engineering processes, their integration into enterprise operations, and their systematic improvement.

Standard curricular and reference material are available for a limited subset of engineering processes (defined as sequences of tasks, including drawing, analyses, and other discrete steps in engineering processes), for example design [1], and systems engineering [2]. This material tends to reference an “ideal state” of the process, rarely reflected in actual practice. Processes are often ad-hoc and experience based, making them difficult to teach, transfer, or coordinate. Process improvement techniques in engineering practice are focused on defining and standardizing the real processes [3]. They are often met with skepticism by engineers (both students and professionals) who are highly trained in the technical aspects of their work and see “process” as a constraint on their creativity and professionalism. This compounds the challenges for educators: How can students be given experience in, or at least a feel for, the messy realities of engineering processes? How can practicing engineers be convinced that processes can be analyzed and improved?

Simulation-Based Education

Simulations are a possible response to this challenge. Internships and other field experiences are the ideal method for exposing students to the complex and highly variable realities of engineering practice, but these are not practical for shorter educational experiences. Even if available, it is unlikely that an internship experience would allow students to change the engineering processes and observe the results! We hypothesized that simulations can be used to: 1) provide a realistic context to students, and a credible approximation of their work environment to practicing engineers, 2) teach implicit, experiential lessons in the holistic, system-spanning nature of both existing practices and the effects of changes, 3) aid experiential learning of process analysis and transformation tools, by using the simulation as a practice field, and 4) increase student involvement and enthusiasm for the material. It was assumed that simulations would have additional benefits (e.g. that non-traditional learning styles would be engaged, that teamwork and collaborative learning would be fostered, etc.), but these were not pursued as deliberate goals.

There is a small but fairly definitive literature that indicates that simulations and “games” help students comprehend material better than lectures or non-participatory graphical presentations. Controlled studies of learning of geology and cell biology [4] and electromagnetism [5,6] have shown students who learn through a computer simulation environment have better knowledge retention than those learning through lecture or static web-based learning. Computer “games” have also been shown to improve outcomes measured by behavior—students learning through simple games are more likely to eat healthy foods [7], and are more likely to take necessary medicines [8], than those instructed with lecture or reading materials.

This literature concentrates on specific desired outcomes or learning points, and (like most of the other literature in the field) uses computer-based simulations or games. It is, however, reasonable to assume that the goal of
increasing comprehension of the curriculum can be obtained. The goal of creating a context, i.e. a mental model of what the material is actually for, is supported in literature as a goal [9], but there are no controlled studies the authors are aware of proving that simulations are a good way of achieving this goal. Creating a practice field for experience through simulations is also supported in the literature, at least as a goal [10]. There is good evidence that a good simulation will get students involved and engaged with the material (or at least with the simulation) [11] but this literature is mostly focused on computer games without regard for educational utility.

The literature is supportive of our hypotheses, but there are not direct parallels between the situations covered in the literature that we are aware of and our complex, multifaceted, real-world simulation. There is also very little information available on the specific problems of teaching “lean” knowledge. As pointed out by Murman et al. [12], Lean Thinking is “a field that is based upon knowledge gained from practice—as contrasted with traditional engineering disciplines that are based upon knowledge from science and mathematics.” This puts particular emphasis on practical demonstrations that can be used to impart this kind of knowledge with some credibility.

Existing examples tend to be demonstrations (as opposed to full simulations with many options to affect the simulated enterprise), and tend to focus on a single learning point. Included in this category are the “Beer Game”[1] and other simple games that demonstrate the effect of single effects on simple processes. Efforts with goals similar to ours are ongoing, such as simulations adapted to teach lean manufacturing [13], or created for lean shipbuilding [14].

**LEAN ENTERPRISE VALUE SIMULATION**

The current work, although applicable to any facet of engineering process education, concentrates on the teaching of lean process improvement to engineers. Lean principles are rooted in the Toyota Production System [15]. They have been applied in many manufacturing, service and educational organizations. To be effective, lean thinking should be implemented across a given enterprise leading to a lean enterprise [16]. Teaching lean principles in the context of complex aerospace enterprises has proved to be extremely challenging. Students need to gain an intuitive understanding of complex enterprises, their intrinsic challenges, and their specific problems, before they can make sense of the concepts of lean transformation in this context. Almost all existing lean teaching materials are focused on applying lean practices to the much simpler and easier-to-understand context of factory-floor processes and their improvement.

In response to this challenge, a team at the Lean Aerospace Initiative created the Lean Enterprise Value (LEV) simulation. The simulation encompasses the lifecycle of an aircraft product, ranging from design and procurement through production and after-market service and support. It comprises multiple inputs and outputs, practices, and stakeholders acting simultaneously to achieve enterprise-level objectives (see Figure 1). Participants must identify not only how to improve the mechanical aspects of their processes, but also the more complex challenge of how to interact with elements of the enterprise outside their control, on mechanical, financial, and human levels. It is a practice field for lean tools such as value stream mapping, kaizen improvements, standard work, single piece flow, and kanban inventory control. The multiple “moving” parts and interdependencies in the simulation ensure that participants must work to master not only their own local tasks, but also to understand mechanisms underlying enterprise success. This adds important social and temporal elements to the overall learning experience.

The simulation consists of basic modules (manufacturing, supply, engineering, and product support) which can be assembled in a number of ways to represent various enterprise architectures. Basic process capability is simulated using sand timers. Process variability is simulated using dice. Lego® aircraft, paper forms, a spreadsheet-based economic system, and other props fill out the immersive experience of the simulation.

The students work for 12-minute rounds building as many aircraft as they can within the constraints of the system. They must manage an inventory of parts, and order them using an initially clumsy system of ad-hoc paper orders. They are also initially restricted to a fixed and unbalanced work load among the various stations, and the Lego airplane they are building initially is a poor design for both manufacturing and customer satisfaction. At the end of each round, students report their production and financial results, and then use various lean tools to diagnose, and possibly fix, the problems of the enterprise.

The LEV simulation has been used since its creation in 2002 in over 100 educational and training events, in university, continuing education, and industrial training settings, and in many variations and customizations. Here, we will concentrate on two cases: the use of the manufacturing table and simplified supply chain in an elementary course in enterprise lean, and the use of the full simulation in an advanced course in lean concepts and tools for enterprise change leaders.

**LEAN ACADEMY MANUFACTURING SIMULATION**

The LAI Lean Academy Course® is a beginning level course in lean focused on the enterprise (as opposed to factory floor) level for aerospace industry interns, students, and employees without lean experience. It has also been adopted by several universities for use in senior or graduate-level classes in engineering or business,

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1 See http://supplychain.mit.edu/games/games.asp
2 See http://lean.mit.edu/; click Products, then LEV Simulation
3 See http://lean.mit.edu/leanacademy
For the Lean Academy, a simplified version of the LEV simulation was created. Four or five teams of 6 students compete to produce Lego aircraft. The simulation includes a manufacturing table, simplified supply chain, a simple financial system, and an abstract engineering capability.

The simulation is used for 76% of the teaching time (5.5 out of 7.25 hours, excluding breaks and administration) of a single day of the 3-day Lean Academy. In the early stages, students familiarize themselves with the simulation mechanics, stabilize production, and generate financial data. They are given a short lecture on lean tools and then do an analytical exercise on the enterprise. The outcome is a value stream map that follows the value flow from the nominal decision to build another airplane, through the inventorying and ordering of the parts, to the assembly of the plane. It includes key data—the amount of time spent at both the mandated tasks and the “wasted” time spent on paperwork, checking inventory, etc.

Having analyzed the system, the students use lean principles such as 5S, visual control, standard work, takt time, balanced single-piece flow, and elimination of non-value added tasks to improve the initial state. The simulation allows a very large number of possible options at this stage. The major categories of improvement actions for this stage of the simulation are shown in Table 1, with their corresponding lean principles, and typical student actions.

Typically, the first set of improvements allow the students to achieve a 50% or better increase in production rate. This improvement is, however, almost never achieved immediately. The students get a visceral lesson in the “worse-before-better” effect. The disruption caused by the change, and the fact that work habits and relationships (particularly in the supply chain) must change to take advantage of the new state, mean that additional effort is required.

### Table 1. Typical Lean Improvements on the Simulation

<table>
<thead>
<tr>
<th>Simulation Improvements</th>
<th>Lean Principles</th>
<th>Typical Student Actions</th>
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<tbody>
<tr>
<td>Organize Activity</td>
<td>5S, Visual Control, Standard Work</td>
<td>Clean up worksite, organize inventory, standardize sequence of ordering, assembly, and paperwork</td>
</tr>
<tr>
<td>Balance Workload</td>
<td>Takt time, Single-piece Flow, Balanced Work</td>
<td>Move work between plants to balance work at 120 sec and 12-13 parts</td>
</tr>
<tr>
<td>Change (improve, eliminate, or move)</td>
<td>Eliminate Unnecessary Tasks, Single-piece Flow, Just-in-Time Delivery</td>
<td>Demolish “warehouse;” freed student moves orders and parts</td>
</tr>
<tr>
<td>Modernize parts order system</td>
<td>Eliminate Unnecessary Tasks, Standard work</td>
<td>Upgrade parts ordering system and standardize orders to single-plane sets</td>
</tr>
</tbody>
</table>

A second round of improvements introduces the Lean Engineering practice of Design for Manufacturing and Assembly (DFMA) in a simplified form. The students are allowed to redesign the aircraft for increased product quality and reduced part count. They are not allowed to change the exterior mold line, however, putting a constraint on the solution set, and making cooperation with the suppliers vital.

At this time, the students are also stressed by “changes in the market.” The demand for planes goes way up (to 12 planes per round) but the price that the customer is willing to pay goes down by about 20%. This provides further...
motivation to both redesign the aircraft, and assure a smooth transition to the new state.

Evaluation

The Lean Academy course modules are assessed by the students using daily feedback sheets which provide both quantitative and qualitative (comments) feedback. The student feedback indicates overwhelming satisfaction with the simulation experience. Figure 2 shows the quantitative feedback results collected from 6 academies with a total of 194 responding students. The students were asked to rate each teaching module or activity in the Lean Academy on a scale from -2 to +2, where -2 meant the module “actively detracted from the experience” and +2 meant the module “provided positive reinforcement of the concepts.” The simulation is compared to other active participation modules, and to lecture-based modules. The circles represent the mean score from 194 responses in each category, with the size of the circle approximately reflecting a 90% confidence interval. The bars show the range from the highest-scored individual activity or lecture to the lowest within each category. Clearly, the simulation rated significantly higher in student satisfaction than the other types of teaching modules.

The satisfaction with the simulation was consistent across all sites, and was not significantly affected by variation in instructors and facilitators. This is in contrast to the relative ranking of the lectures and other activities, which did vary by site, and the satisfaction scores of the lectures, which were affected by the identity of the lecturers.

The feedback collected included an open-ended question “what did we do well today?” This question was asked daily. Of 182 surveys distributed on the day of the simulation, 58% (106) had answers referring to the simulation. These were broken down into five categories, selected based on a preliminary scan of the comments. The first was “good” comments, complementing the simulation itself but not specifying why. Next were comments on the students’ feelings about the simulation experience, including words such as “exciting,” “stimulating,” or “fun:

- I really enjoyed the simulations with the Legos. This made time fly.
- ... SO good and SO cool. One of the most enlightening engineering experiences I’ve had.

Next were comments that indicated the simulation helped reinforce, illuminate, or clarify the course material:

- ... helped with application of what we learned in lecture
- It took a while to get the concepts but it finally clicked during the 2nd segment of the simulation

Next, comments that indicated that hands-on learning, practice, or exercise helped:

- Hands on – Excellent. Telling someone how something works is fine. Having someone do it teaches it
- LOVED the simulations. Figuring stuff out yourself makes things make much more sense

Finally, comments on interactions fostered with the learning group and/or the instructors:
- Created a good sense of camaraderie

The results are shown in Fig. 3. The results indicate that, asked an unbiased question, significant numbers of students volunteered that that the simulation met the goals of increasing comprehension, learning through hands-on experience, and increased enthusiasm and personal involvement. The selection and coding of comments was done informally, by a single investigator, so these results are not rigorous, but they do indicate student satisfaction with the simulation, and indicate that, at least for some students, the learning objectives of the simulation were met.

LEV SEMINAR SIMULATION

The Lean Enterprise Value seminars use various configurations of the simulation as the centerpiece of advanced classes in lean process improvement. Seminars range from one-day seminars build around the engineering simulation, to two-week six-sigma training using the full simulation as a practice field for a variety of lean and six-sigma tools. More typical is a 2-2.5 day seminar built around the full simulation (Fig. 1), designed to teach lean enterprise concepts to change leaders. The first day is spent reviewing traditional lean concepts, and improving the local
The later part of the course is spent on lean enterprise concepts, and improving the global performance of the simulation under challenges to the entire organization (such as redesigning the aircraft). This is much harder, as it requires close collaboration of the entire class, and planning and communication across the entire simulated enterprise. Typical explicit student actions are shown in Table 2. Also important are the implicit lessons the students get from actually having to execute these improvements in a complex environment. Communication, coordination, synergies, and synchronization are concepts that are easy to lecture on, but difficult to teach. All are vital to the success of the simulated enterprise changes, and the students get powerful experiential lessons in these concepts in the simulation.

<table>
<thead>
<tr>
<th>TABLE 2. LEAN ENTERPRISE IMPROVEMENTS</th>
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<tr>
<td>Simulation Improvements</td>
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<tr>
<td>Airplane may be redesigned within a constant exterior mold-line</td>
</tr>
<tr>
<td>Balance Workload between Facilities (again)</td>
</tr>
<tr>
<td>Change (improve, eliminate, or move) Facilities</td>
</tr>
<tr>
<td>Further Modernize Supply Chain</td>
</tr>
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</table>

Evaluation

The LEV seminars have been given in a variety of forms, at a variety of locations, and with a variety of evaluation techniques. We have given the seminar over 26 times, and it has also been adopted by several corporate and university-run training programs. Our qualitative assessment is that it is the only way to transmit the complex ideas of enterprise level lean to an often skeptical or naïve audience, and a very good context for the learning of lean tools and techniques. It benefits from customization for each audience and situation. It has been particularly useful for just-in-time training of teams about to embark on improvement events, but in these cases it has been especially valuable to customize the lessons so that they closely match the upcoming work.

This has presented a barrier to systematic quantitative evaluation. A set of five seminars given in 2005 and 2006 used the same basic scenario. The participants were asked to rate the course components and their perceived learning using the same questionnaire. The major course learning components (simulation, lecture, and peer interaction) were rated on a 1-5 scale; with one meaning “didn’t learn much” and 5 meaning “learned a great deal.” Ninety-six students answered these questions. The students were asked “compared to other courses you have taken, how effective was the course for teaching” factual information, concepts and ideas, and tools. Again, a 1-5 scale was used, with one meaning “much less effective” and 5 meaning “much more effective.” Sixty-two students answered these questions. As the simulation and related exercises took 85% of the seminar time (15.25 out of 18 teaching hours), the simulation was assumed to be the predominant factor in this assessment.

The results are shown in Figs. 4 and 5. The bars in this case represent 90% confidence intervals. The overall satisfaction with the seminars was high, with both the simulation itself and the peer learning ranking significantly above the traditional content. The structure of the longer LEV class and the more complex interactions built into the simulation experience encourages greater interaction among students for problem-solving and solution development. The students found the seminars effective overall, with a significantly higher score for being effective at teaching concepts and ideas. Feedback data from open-ended evaluation questions from the LEV seminars are typical of those shown for the Lean Academy classes.
A final, more direct measure of learning outcomes was collected as a byproduct of a version of the seminar that concentrated on Enterprise Value Stream Mapping and Analysis (EVSMIA).\textsuperscript{6} As part of a tool exercise, students were asked to carry out a simplified form of the Lean Enterprise Self Assessment Tool (LESAT),\textsuperscript{7} dubbed SIMSAT. The students were asked to assess the simulated enterprise on a total of 21 business process metrics near the beginning of the class, and again at the end. The metrics comprise general categories of Lean Transformation (e.g., strategic planning, value stream focus, lean structure and behavior, lean transformation plan, continuous improvement focus), Life-Cycle Processes (e.g., business development, program management, requirements definition, product and process development, supply chain management, production), and Enabling Infrastructure (e.g., finance). The students were asked both to rate the existing state of the simulated enterprise and to assess the importance of each of the metrics. This exercise was carried out in 3 seminars; a total of 32 students submitted usable data. A comparison was made between the students’ perception of the importance of the metrics at the beginning and end of the class; the difference was taken to be a direct effect of the in-class learning. One significant pattern did emerge. The biggest change in the students’ perception of importance took place for three characteristics:

- Leveraging the extended enterprise
- Relationships based on mutual trust
- Enterprise-level lean transformation plan

These are interesting measures in that they reflect a perspective on the role of lean tools and practices at the system level. It should be noted that the students receive a lecture on lean enterprise (i.e., system-level) concepts at the beginning of each seminar, but typically don’t demonstrate deep understanding of these more complicated concepts until after they have gone through the full simulation experience. While the evidence is still being collected, both limited survey data and anecdotal experiences with the students in each class suggest that this simulation-based instruction method is effective in teaching lean enterprise concepts.

CONCLUSIONS

This paper has presented findings from classes using simulation-based instruction to teach relatively complex engineering processes and to provide a more sophisticated awareness of the role of those processes in an organizational context. Qualitatively, it was our observation that the teaching is very effective. Quantitatively, while the data are limited by small and non-systematic samples, the proposed hypotheses on the effectiveness of simulation-based training for teaching engineering processes were supported.

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AUTHOR INFORMATION

Hugh McManus, Senior Special Projects Engineer, Metis Design, 10 Canal Park Suite 601, Cambridge MA 02141, hmcmanus@mit.edu

Eric Rebentisch, Research Scientist, Massachusetts Institute of Technology, 77 Massachusetts Ave. Room 41-205, Cambridge MA 02139, erebenti@mit.edu

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