

# TEACHING LEAN THINKING PRINCIPLES THROUGH HANDS-ON SIMULATIONS

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## **Abstract**

The teaching of Lean Enterprise Thinking in the aerospace context requires that students understand a complex subject— aerospace enterprises and their transformation—in a deep and intuitive way. Without this context, the lessons of the LAI Lean Academy Course<sup>®</sup> will make little sense. A rich simulation of an enterprise with a structure and problems typical of the US aerospace industry is used as a teaching tool. The simulation allows students to understand Lean Thinking at an intuitive level, and practice lean tools in a realistic setting. The simulation enables a CDIO approach (in this case, *Comprehend*, Design, Implement and Operate), by having the students take two iterations through a CDIO process to transform the simulated enterprise from an inefficient legacy state to a high performance future state (x3 to x6 production using the same resources). The simulation and its teaching goals are described, with reference to the limited literature on simulations in education. The process used in the simulation is then described in a CDIO context. Finally, the success of the simulation is evaluated using limited quantitative and more extensive qualitative data. It is found that the simulation is a powerful learning tool and a key component of the LAI Lean Academy.

*Keywords: Lean Education, Simulation, LAI Lean Academy, Active Learning*

## **The Lean Academy Simulation**

Lean principles are rooted in the Toyota Production System [1]. 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* [2]. Teaching lean principles in the context of complex aerospace enterprises has proved to be extremely challenging, especially for engineering students who are not used to abstractions such as enterprises and process flows. Students need an intuitive understanding of complex enterprises, their intrinsic challenges, and their specific problems, before the concepts of lean transformation can make sense in this context. Almost all existing teaching materials are focused on the much simpler and easier-to-understand context of a factory floor.

In response to this challenge, a team at the Lean Aerospace Initiative created the Lean Enterprise Value (LEV) simulation.<sup>1</sup> Participants fabricate parts, process engineering design jobs, assemble, and support a fleet of Lego® aircraft, to satisfy customer and corporate demands. Each participant is in charge of a facility: an assembly plant, subcontractor fabricating plant, product development department, or service and support depot. A realistic economic system allows participants to track their performance and justify their decisions as they progress on their lean enterprise journey. During the course of the simulation, participants learn advanced lessons in applying lean at the enterprise level, quantifying the value of lean improvements, and managing change in a complex, interdependent enterprise. The LEV simulation is, intrinsically, a tool for teaching enterprise-level lean thinking. 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 also a practice field for lean tools such as value stream mapping, *kaizen* improvements, standard work, single piece flow, and *kanban* inventory control.

For the LAI Lean Academy Course, a simplified version of the LEV simulation was created. Teams of 6 students (4-5 teams in a typical class) compete to produce Lego aircraft. The simulation includes a 4-station process for creating Lego aircraft, a two-step supply chain (including a warehouse and a remote supplier), a simple financial system, and an abstract engineering capability. The basic process flow of the simulated facility is shown in Figure 1. Five students and a facilitator (the “customer” in the flow chart) sit at a manufacturing table. Four of the students have manufacturing jobs. One student plays the part of the parts buyer; he or she accepts parts orders and conveys them to the supplier, who sits at a distant table with all of the suppliers for the other tables. This sets both a physical and psychological barrier to integration of the parts supplier into the enterprise team.

Each student sit at a “facility” which has all of the equipment and instructions necessary for them to participate in the simulation. Figure 2 shows a manufacturing facility (consisting of a visual work package showing what Legos to assemble, ordering forms and a storage area for parts, a “factory” with assembly rules and timers, and financial reporting forms), a supplier facility (consisting of order fulfillment paperwork and parts bins, from which the student must fill orders), and the Lego aircraft produced. The students at the manufacturing stations use sand timers to represent the underlying capability of the manufacturing plant; this prevents the simulation from degenerating into a race or favoring students with high manual dexterity or Lego experience. As can be seen in Figure 1, the workload is highly imbalanced (some students must assemble many more parts, and/or wait for a much longer timer) in the initial state.

A simple financial system tracks the income from selling aircraft, penalties due to low quality manufacture (i.e. incorrectly assembled aircraft), the fixed cost of the facilities, the variable cost of the parts used (or scrapped), and, later in the simulation, the cost of capital improvements. Engineering (which is explicitly included in the full LEV simulation) is included as an overhead charge—its usefulness becomes apparent only late in the simulation. The financial data is collected at the end of each round and recorded on either a simple paper form or a small Excel® spreadsheet. Figure 3, taken from instructional material, illustrates the financial system.

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<sup>1</sup> See <http://lean.mit.edu/>; click Products, then LEV Simulation

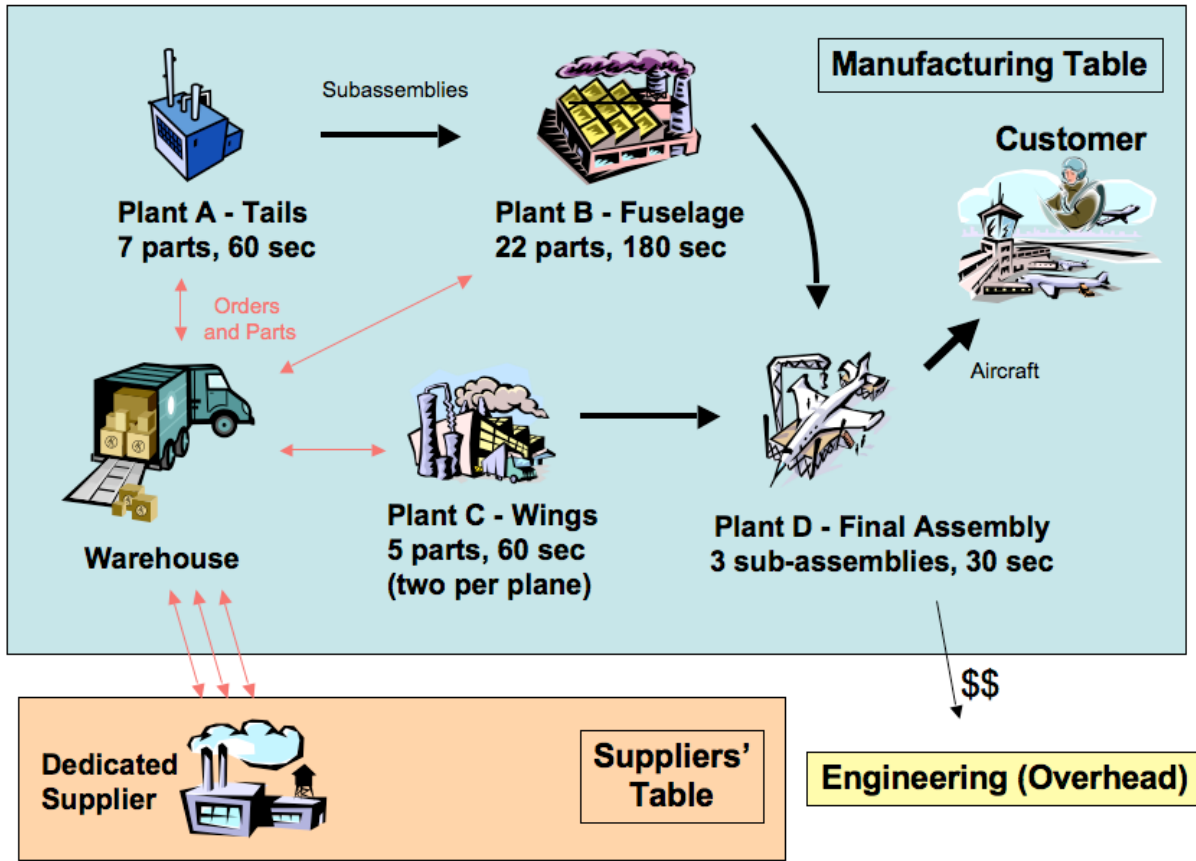


Figure 1. Process Map of Simulation in Initial State



Figure 2. Simulation Equipment – Manufacturing and Supplier Facilities, Lego Airplane

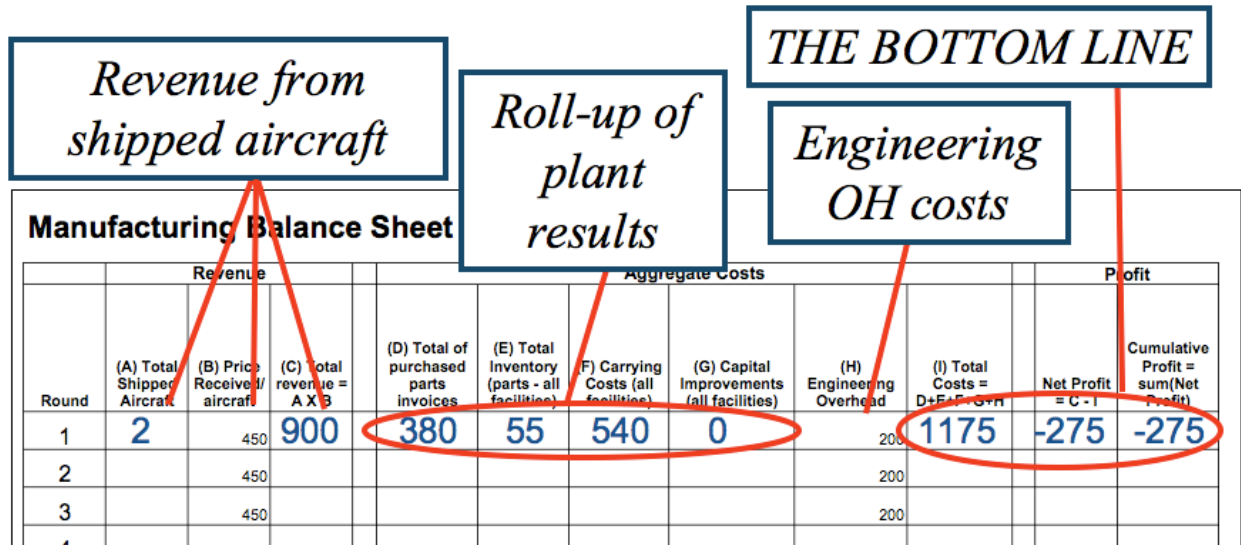


Figure 3. Simulation Financial Metrics as Illustrated in Instructional Materials

The students work for 12-minute rounds building as many aircraft (Figure 2) as they can within the constraints of the system, which are numerous. They must manage an inventory of parts, and order them using an initially clumsy system of ad-hoc paper orders, working through a middleman (the warehouse). They are also initially restricted to a fixed and unbalanced work load among the manufacturing plants, and the Lego airplane they are building initially is a poor design for both manufacturing (it has too many small parts) and customer satisfaction (it has a mechanically weak tail section, and is too expensive, partially as a consequence of the large number of parts).

### Using the Simulation

The simulation is used for more than half of the teaching time of a single day of the Lean Academy. The simulation is run in 12-minute rounds, during which the students fully immerse themselves in the simulated enterprise, and try to meet customer demand for the Lego aircraft. The students do a round of the simulation to learn its mechanics, and another to stabilize production in the initial state. Typically, they are able to produce 2-4 aircraft in the second round. After collecting financial data (initially dismal—the numbers in Figure 3 are typical) they hear a short lecture on lean tools and then do an analytical exercise on the enterprise. A somewhat idealized outcome of such an exercise is shown in Figure 4. This is a value stream map of the facility shown in Fig. 1. It differs from Fig. 1 in following 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—in this case, the amount of time spent at both the mandated tasks (i.e. the hourglass time) and the “wasted” time spent on paperwork, checking inventory, etc.

Having analyzed the system, the students use lean principles such as 5S<sup>2</sup>, visual control, standard work, *takt* time, balanced single-piece flow, and elimination of non-value added tasks to improve

<sup>2</sup> 5S is an approach to workplace organization. Its name comes from 5 Japanese words, interpreted in English as Sort, Straighten, Scrub, Systematize, and Standardize.

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. Note other improvements are possible (i.e. increasing capacity through large capital investments) but they are not good answers. The students are mentored away from poor solutions (using, for example, simple calculations using the financial system) but many good-to-excellent solutions are possible.

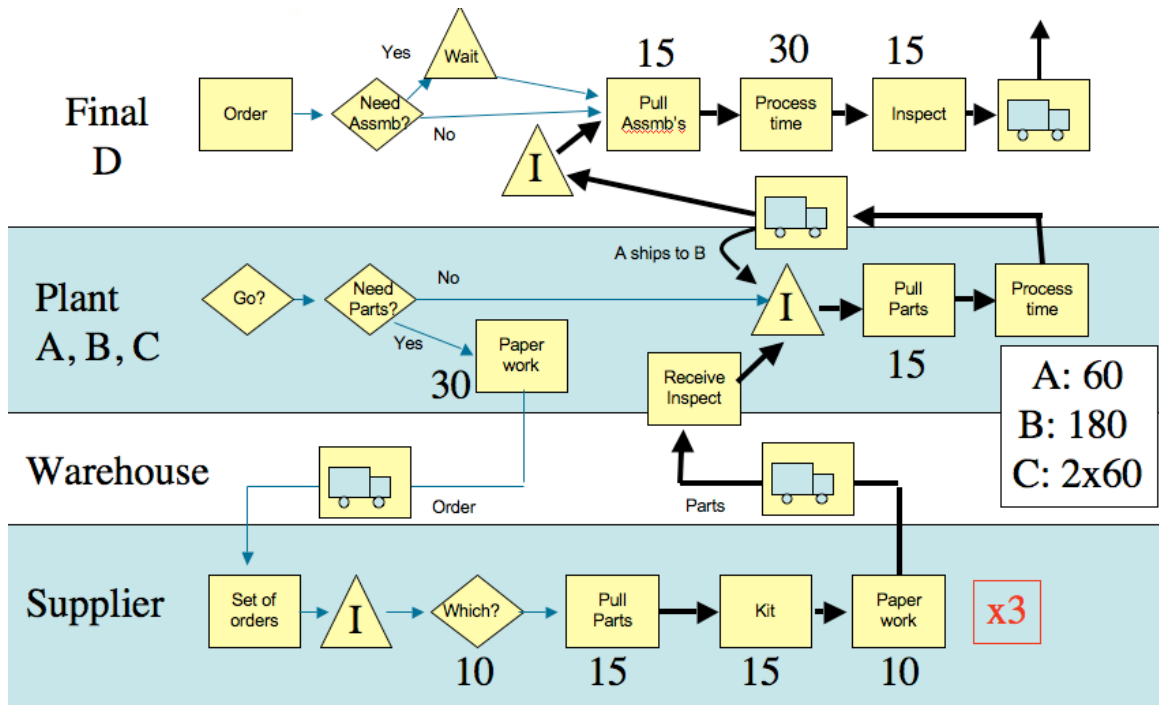


Figure 4. A Value Stream Map derived from the Simulation Processes. Data are Times in Seconds.

Table 1. First Set of Lean Improvements

Simulation Improvements	Lean Principles	Typical Student Actions
Organize Activity	5S, Visual Control, Standard Work	Clean up worksite, organize inventory, standardize sequence of ordering, assembly, and paperwork
Balance Workload between Facilities – this requires an “engineering request” (approved by instructor)	<i>Takt</i> time, Single-piece Flow, Balanced Work	Move work between plants to balance work at 120 sec and 12-13 parts
Change (improve, eliminate, or move) facilities – this requires “corporate approval” (also by instructor)	Eliminate Unnecessary Tasks, Single-piece Flow, Just-in-Time Delivery	Demolish “warehouse;” freed student moves orders and parts
Modernize parts order system by eliminating paperwork – requires “corporate approval”	Eliminate Unnecessary Tasks, Standard work	Upgrade parts ordering system and standardize orders to single-plane sets

Typically, the first set of improvements allows the students to achieve a 50% or better increase in production rate, to 5-6 aircraft. 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. This is almost entirely *interpersonal* effort, involving communication, understanding roles and responsibilities, and synchronizing and coordinating actions. It is by working together to implement the improvement project, *and operating the improved enterprise*, that the necessary team bonds are built that allow the system to actually function up to its capacity.

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, as they have the capability (not hidden, but not pointed out to the students either) to supply large Lego bricks that can reduce the number of total parts necessary to produce the aircraft. These have the added benefit of eliminating joints and hence weak points in the design, increasing “customer satisfaction.” In the interest of pedagogy, the realism of the full LEV simulation is considerably relaxed—the redesign effort is assumed to proceed quickly and to be paid for out of engineering overhead. In the full LEV simulation, considerable time, effort, and expense go into the simulated engineering process.

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. Finally, the students usually notice (and are mentored to the point if they do not) that the supplier will be severely stressed by the parts demand for 12 airplanes, and so cooperative work goes into perfecting the supply chain, usually involving a formal implementation of a *kanban* inventory management system, managed by the former warehouse person. Table 2 summarizes the options and typical choices made by the students.

Typically, the second set of improvements goes much smoother, as the students have built up experience in enterprise change and have developed effective working relationships. The students actually get quite competitive at this stage, motivated to bend the rules to produce the absolute maximum number of aircraft. The final result, which almost always takes only one round to achieve, is 8-14 aircraft, with a “theoretical” production of 12 considered ideal. Producing 14 aircraft involves no cheating, but it does require bending several rules—an amusement for the class, but not a good lesson in standard work or working to customer demand.

The simulation concludes with the collection of a final round of financial data, showing the impact of the lean improvement on the “bottom line” even when improvement costs are taken into account. Figure 5 shows a typical group’s production and financial results in the five rounds that make up a typical simulation day.

Table 2. Final Set of Lean Improvements

Simulation Improvements	Lean Principles	Typical Student Actions
Airplane may be redesigned within a constant exterior mold-line	Lean Engineering, DFMA, Supplier Integration	Reduce part count by 10 (to 28 per plane) using large Lego blocks available to suppliers
Balance Workload between Facilities (again)	<i>Takt</i> time, Single-piece Flow	Move work between plants to balance work at 60 sec and 7-9 parts, including using excess capacity at final assembly to install some exterior parts (e.g. landing gear)
Change (improve, eliminate, or move) Facilities	<i>Takt</i> time, Single-piece Flow	Students find they must <i>increase</i> capacity at some manufacturing plants (but can now justify it economically)
Further Modernize Supply Chain	Standard work, Just-in-Time, <i>Kanban</i>	Implement a two-bin <i>Kanban</i> inventory management system throughout enterprise

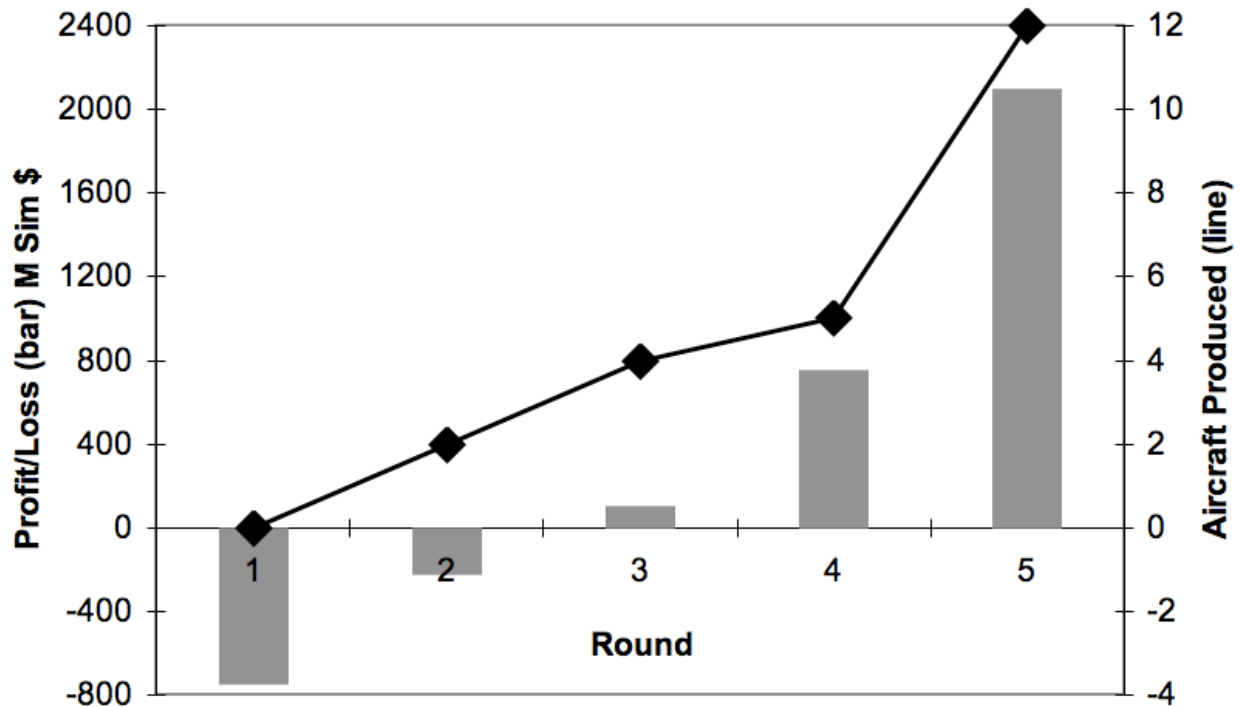


Figure 5. Production and Financial Performance for a Typical Team.

## Simulation-based learning

The simulation is used as a tool for teaching complex lean concepts. At its most basic, it is a mode of active learning, discussed in the companion paper by Candido *et al.* [3]. More specifically, the goals for the simulation include 1) increased comprehension of the curriculum, 2) better understanding of the context and holistic, system-spanning nature of the material, 3) learning through experience via use of the simulation as a practice field, and 4) increased student involvement and enthusiasm for the material. It was assumed that the simulation 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 second 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. The situation with the third goal, of creating a practice field for experience, is also supported 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 approach, but there is not direct parallel between the situations covered in the literature that we are aware of and our complex, multi-faceted, real-world simulation. There is also very little information available on the specific problems of teaching “lean” knowledge. As pointed out in the companion paper by Murman *et al.* [12], Lean Thinking is “a field that is based upon knowledge gained from practice—as contrasted to 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” [13] which demonstrates supply chain instability, and dice games that demonstrate the effect of variability on simple processes [3]. Efforts with goals similar to ours are ongoing, such as simulations adapted to teach lean manufacturing [14], or created to teach lean shipbuilding [15]. Simulations have also been used effectively to teach design concepts and processes [16]. A colleague has recently created an ingenious classroom exercise that allows students to redesign a fairly complex system—the students use lean methods to optimize *the design class they are taking* based on the needs of the project selected for the term [17].



## **Simulations as a Practice Field for CDIO learning**

Given the lack of direct guidance from literature, the simulation was created based on experience with project-based learning that is at the heart of the CDIO method. As a consequence, there is a very strong link between the simulation and CDIO concepts. The link is reinforced by the fact that most process improvement methods<sup>3</sup> themselves suggest a set of actions that sound very much like CDIO. One of the earliest examples is the Plan-Do-Check-Act (PDCA) cycle pioneered in the 1930s by Walter Shewhart [18] and later associated (as the Plan-Do-Study-Act, PDSA) with the work of W. Edwards Deming [19]. The Six-Sigma method encourages a Define-Measure-Analyze-Improve-Control (DMAIC) cycle [20]; Process Reengineering suggests Mobilization-Diagnosis-Redesign-Transition cycles [21]. The simulation is actually taught around a similar set of actions that are deliberately identical to none of the above to avoid dogmatic debates. Here, we will cast the simulation teaching in terms a Comprehend-Design-Implement-Operate cycle.

### ***Comprehend***

Rather than Conceive (the appropriate first step in a new design) the students must come to an understanding of the current state of the process and the (unmet) user needs. The students first use value stream mapping to understand the basic flows of material and information through the system. This information must then be quantified by collecting data on key aspects of the system. This data includes the time that it takes to do various steps; the capacity of various steps; the user needs; and evidence of process pathology such as inventory and idle time. The students are challenged to discover this data from within the simulation environment, much as design course students must “data hunt” before serious Design work can begin. The artifact from this step is a value stream map—an idealized version is shown in Figure 4.

### ***Design***

The challenge is now for the students to redesign the system to meet user needs. The analog to original design work is fairly strong at this step. The students need to understand and quantify user needs, brainstorm possible approaches to the problem, understand the “physics” of the environment, and analyze proposed solutions to confirm that they are feasible and meet user requirements. In this case, the user needs are expressed in terms of quality products produced by the system at an acceptable rate and price; the brainstorming is open ended, although somewhat constrained by the simulation; the physics are the limits of the simulated system, most of which have been discovered in the previous phase; and the analysis is in terms of production rates and costs, including the costs to change the system. The students are encouraged to trade several design options, selecting one or two that can meet user needs at minimum cost.

### ***Implement***

The idea behind this step is conceptually similar to that of a design class: that the actual implementation of the (re)design contains a different set of lessons than its analysis. In a hardware-oriented design the implementation details are often physical. In the simulation, the mechanical changes (i.e. moving capacity from one station to another) are straightforward; it is

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<sup>3</sup> There are several competing methodologies for the improvement of existing processes. Their differences are beyond the scope of this paper; they all share the purpose of understanding an existing process, designing and implementing improvements, and following up in some way.

the organizational and people issues that create extra learning from the Implement phase. Just as a physical design that looks good on paper may run into difficulties when complex parts are machined or small bonds are expected to take large loads, the organizational designs are often challenged by unanticipated difficulties like shifting constraints (a new bottleneck appears when an old one is cleared) or communication difficulties (“I was waiting for *you* to order the parts”). In either case, the students learn about both the implementation process itself, and the effects their design had on “implementability.”

### ***Operate (and Iterate)***

The ultimate payoff from any design is its operation to achieve an end. This is perhaps the one lesson that is *easier* to understand in a production system than a piece of hardware, as the output of the operation of the simulated production system is very tangible. The students learn a continuation of the implementation lesson—that even when a new state is achieved, it needs constant “care and feeding” to perform as designed. Again, this tends to involve communication issues such as spotting, communicating and fixing anomalies in a timely fashion.

In the simulation, the students go through two full CDIO cycles, so the intermediate Operate stage becomes the basis for the next round of analysis and improvement. Until the improved system is actually in operation, the Comprehend step in the next cycle has little meaning. This cycling between improvement, stable operation, and the next round of improvement is at the heart of Lean and other continuous process improvement techniques, and understanding it experientially is a major take-away for the students. The second operating experience, on the other hand, is mostly an enthusiasm builder—the students get the pleasurable experience of “flow” in both the lean production and psychological senses of the word [22].

### **Evaluation**

The Lean Academy course modules are assessed by the students using daily feedback sheets which provide both quantitative (-2 to +2 satisfaction scoring) and qualitative (comments) feedback. The student feedback indicates overwhelming satisfaction with the simulation experience. Figure 6 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 not only any other type of activity, but also any individual activity.

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 strongly affected by the identity of the lecturers.

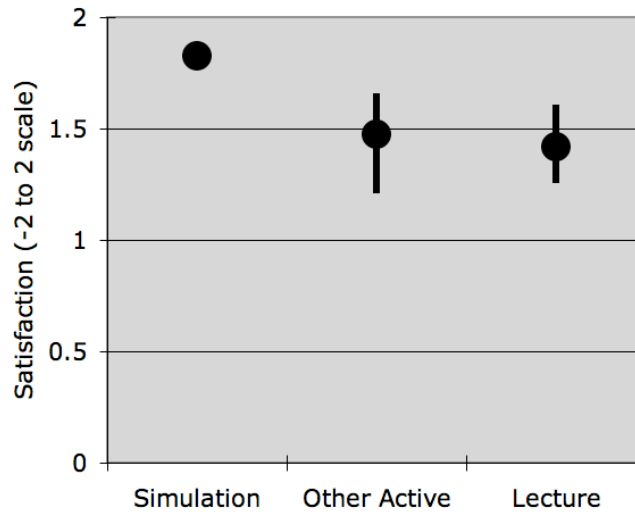


Figure 6. Relative Satisfaction (-2 to 2 scale) of Students

The qualitative feedback indicated that the learning objectives of the simulation were met. The feedback collected included an open-ended question “what did we do well today?” Of 182 surveys distributed, 42% of students either did not return the survey, left the question blank, or mentioned something other than the simulation in this category. 58% (106 written responses) explicitly mentioned the simulation. The comments were broken down into five categories, selected based on a preliminary scan of the feedback. 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 2<sup>nd</sup> 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 Figure 7. The results indicate that, asked an unbiased question, significant numbers of students volunteered that the simulation met the goals of increasing comprehension, learning through hands-on experience, and increased enthusiasm and personal involvement. These are three of the four goals listed above. The fourth, better understanding of the context and holistic, system-spanning nature of the material, was not mentioned by any student. The fact that the simulation was done on the second day, when the students were not ready for integrative thinking, may have influenced that result. Also, other context-setting exercises within the Lean Academy (e.g. plant tours) may have overshadowed this function of the simulation.

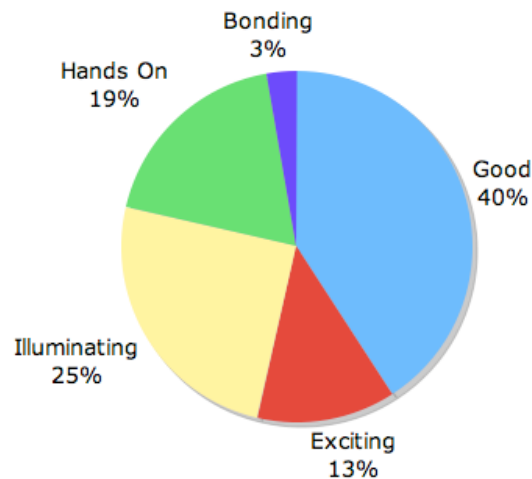


Figure 7. Types of Positive Written Responses Referring to Simulation (N=106)

These results show student satisfaction with the simulation, and indicate that, at least for some students, the learning objectives of the simulation were met.

### Caveats

The first caveat concerns this study more than the simulation. The data used to evaluate the simulation here measured only student satisfaction, not learning outcomes. Outcomes (the VALUE scores) were measured as part of the LAI Lean Academy [3] [12] but they do not distinguish between the learning from the simulation and that from other modules. The best we can say is that the simulation is a highly regarded component of a course with good outcomes.

The simulation is not without cost. The first is literal—it takes around two thousand dollars to collect the necessary materials, and there is some difficulty doing so.<sup>4</sup> The simulation has suffered from one of the lessons it teaches—the dangers of supply chain instability. The necessary Legos are no longer entirely available from the Lego company, and must be procured from the (fortunately thriving) on-line secondary market. Worse is the investment in trained personnel. The simulation requires a facilitator at each of the tables of six students, and a master

<sup>4</sup> On the other hand, this should be contrasted with the expense of creating a computer-based simulation, which is in the millions of dollars for anything beyond a very simple (and therefore not credible) visual simulation.

facilitator to run the whole show. Training a table facilitator requires (typically) experiencing the simulation as a participant, followed by a few hours of follow-on training; training a master requires several experiences as a table facilitator and ideally a session training under an existing master. Much of this difficulty can be traced to the origins of the simulation as a customization of the even more complex LEV training simulation. Several rounds of improvements (mostly simplifications and clarifications) have now been done with the Lean Academy variant, but it is still a complex simulation, not a simple training demo or “game.” This reflects a basic tradeoff in simulation design, in that a simulation of a moderately complex interdependent system (multiple independent activities that must be coordinated) with a realistic context (e.g., industrial process flows and nomenclature, formalized improvement methods, functional financial accounting system, etc.) involves more detail and effort than a simulation designed to focus on meeting a single learning objective.

From the student point of view, the limited negative feedback received illustrates a general point about simulations. In response to the question “what could we do better,” asked at the end of the day on which the simulation took place, only 29% of students volunteered any answer. Of these, more than half were complaints about the simulation mechanics—the clarity of the instructions, the quality of the facilitation, or the availability of needed materials. Most of these complaints came from two sites, one of which suffered a parts shortage due to a misplaced bag of Legos, and one of which suffered from incorrect advice from a few of the table facilitators. Both problems were quickly corrected and had no effect on either the success of the simulation or the satisfaction scores, but they left an impression. The general principle, expressed frequently although, to the knowledge of the authors, unconfirmed by controlled studies, is that educational simulations are not always robust.<sup>5</sup> Small problems can detract from the student experience, and too many problems can “crash” the experience, resulting in frustration instead of learning. Handling problems is highly dependent on skilled facilitators and instructors. The aforementioned parts-shortage problem was actually converted into a learning point about supply chain limitations, the spotting and communication of early signs of difficulties (the suppliers knew they were running out), and adaptable enterprise responses to them. Even with this “save,” the students did notice the unplanned problems and it detracted from the simulation’s credibility.

The remaining complaints illustrate another point. They included some comments that the simulation took too much time, but these comments were balanced by ones that suggested cutting other activities during simulation day to allow *more* simulation time. Several students felt “left out” because they were given supplier positions—a deliberate teaching point designed into the simulation! Finally several students expressed frustration that the other teams indulged in “creative accounting” to make their results look better—again, the dark side (whether or not the accusations had merit) of the deliberate competition set up between the tables. The generalized point is that this sort of activity will always be a balance, with no one solution being ideal for all learning styles and personalities.

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<sup>5</sup> To paraphrase Alex Miller of U. of Tennessee, the author of a product development simulation, simulations “work great, except when they don’t.”

## Conclusions

A complex simulation of an aerospace enterprise is used as a teaching tool and practice field for a class in lean process improvement techniques. The simulation and the way in which it was used were designed with cognizance of, but not direct heritage from, existing work on educational simulations. The intent was for the simulation to provide increased comprehension of the curriculum, context, hands-on experience, and increased student enthusiasm. The process improvement techniques themselves have a systematic, CDIO-like approach. The class did two cycles of lean process improvement, interpreted here as Comprehend, (re)Design, Implement and Operate, on the simulated system. The experience of many classes over several years indicates that the simulation has been very successful. Student feedback reinforces this view; the simulation ranks significantly above all other teaching modules in the class in student satisfaction. Student written comments further indicate that the simulation is meeting its learning objectives. This satisfaction comes at a price in terms of expense and instructor and facilitator effort. The simulation is not immune from known difficulties of simulation-based education; it is vulnerable to disruption by mistakes or poor facilitation, and it cannot simultaneously satisfy every learning style.

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**Hugh McManus** is Senior Special Projects Engineer at Metis Design, applying modern product development, business and technical practices to the aerospace industry. He has pioneered work in the area of lean product development with MIT's Lean Aerospace Initiative (LAI). Hugh leads seminars and workshops, supervises research, and has authored many publications and several major tools for lean transformation. Dr. McManus is currently facilitating transformation projects for the US Air Force with UT Knoxville. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

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**Earll M. Murman** is Ford Professor of Engineering Emeritus at the Massachusetts Institute of Technology, Cambridge, MA. Prof. Murman served as Co-Director of the Lean Aerospace Initiative from 1995-2002 and as Head of MIT's Department of Aeronautics and Astronautics from 1990-1996. In addition to his 26 years in academia, his career includes 4 years at the Boeing Company, 6 years with Flow Research Co., and 3 years at NASA's Ames Research Center. He currently serves as the LAI EdNet Director.

**Alexis Stanke** is a Senior Systems Engineer at Eclipse Aviation, Albuquerque, NM. Dr. Stanke recently received her Ph.D. from the Engineering Systems Division at MIT working on identifying best practices of high performance aerospace programs. Prior to that, she worked with LAI to initiate the EdNet, and she was one of four original developers of the LAI Lean Academy. She also co-authored a lean-based enterprise-wide analysis and strategic planning tool and has helped facilitate the implementation of this tool in conjunction with the full LEV simulation. She is currently applying her experience from inside the product development group at Eclipse.

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