Teaching Lean Thinking Principles Through Hands-On Simulation

Hugh McManus
Metis Design

Eric Rebentisch and Earll M. Murman
MIT Lean Aerospace Initiative

Alexis Stanke
Eclipse Aviation

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This talk presents an overview of the teaching simulation used in 16.660 / 16.853 / ESD.62J Introduction to Lean Six Sigma Methods.

It cannot replace the simulation experience, but outlines the goals, process, and basic lessons of the simulation.

It was written for a conference on “Conceive, Design, Implement, and Operate” (CDIO) teaching methods, and the second half of the talk relates the simulation experience (and this course in general) to the CDIO method.

Overview

• Description of Lean Enterprise Simulation
• Use in Simulation-based learning
• Simulations as a CDIO practice field
• Evaluation of the simulation in the Lean Academy
• Caveats and Conclusions
Simulation Goals

• **Teaching Lean applied to complex enterprises challenges traditional teaching modes**
  - Experience based
  - Depends strongly on complex context not familiar to students

• **Use Simulation-based learning for:**
  - Increased comprehension of the curriculum
  - Better understanding of context and holistic, system-spanning nature of lean changes
  - Learning through experience - a practice field for lean change
  - Increase student involvement and excitement
Simulation Objective: Build Lego Airplane

- Lego aircraft starts as a non-lean product
  - Excessive part count
  - Too many part types
  - Weak tail
- Built in a non-lean way
  - Unbalanced production system (bottlenecks, unused capacity)
  - Long supply chain
  - Excessive paperwork
  - Unclear communication

Lean Academy simulation is a subset of the Lean Enterprise Value (LEV) simulation
Simulated Production System

- Plant A - Tails
- Supplier Quality Representative
- Orders and Parts
- Dedicated Supplier

- Plant B - Fuselage
- Subassemblies

- Plant C - Wings

- Plant D - Final Assembly

- Customer
- Aircraft

Manufacturing Table

Suppliers’ Table
Simulation Features: Visual Instructions

• Shows you how to put a sub-assembly of the plane together
• If organized (as shown) provides a visual cue to obtain needed parts
• Easy to learn
• May be changed
Timers Represent Process Times and Capacity

- Legos are assembled by the pace of an hourglass (time depends on part count)
- Prevents racing, dexterity contests
- Focuses attention on the process

<table>
<thead>
<tr>
<th>Part Count</th>
<th>Hourglass</th>
<th>Sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td></td>
<td>30</td>
</tr>
<tr>
<td>4-7</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>8-13</td>
<td></td>
<td>120</td>
</tr>
<tr>
<td>14-21</td>
<td></td>
<td>180</td>
</tr>
</tbody>
</table>
### Parts Ordering Form

<table>
<thead>
<tr>
<th>Part Description</th>
<th>Color</th>
<th>Size</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick</td>
<td>Light Grey</td>
<td>1x2</td>
<td>3</td>
</tr>
<tr>
<td>Brick</td>
<td>Brown</td>
<td>1x2</td>
<td>2</td>
</tr>
<tr>
<td>Brick</td>
<td>Sand Red</td>
<td>1x2</td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>White</td>
<td>2x2</td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>White</td>
<td>2x4</td>
<td></td>
</tr>
<tr>
<td>Brick</td>
<td>White</td>
<td>2x8</td>
<td></td>
</tr>
<tr>
<td>Plate</td>
<td>White</td>
<td>1x6</td>
<td></td>
</tr>
<tr>
<td>Plate</td>
<td>White</td>
<td>2x4</td>
<td>4</td>
</tr>
<tr>
<td>Plate</td>
<td>White</td>
<td>2x8</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>Black</td>
<td>2x3</td>
<td></td>
</tr>
<tr>
<td>Slope</td>
<td>Black</td>
<td>4x3</td>
<td></td>
</tr>
</tbody>
</table>

To be completed by supplier when order is fulfilled:

| Total number of parts shipped: | 9 |

---

### Supplier Quality Representative

**Supplier**

<table>
<thead>
<tr>
<th>Fulfillment Receipt</th>
<th>Delivered to:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invoice amount:</td>
<td>45</td>
</tr>
<tr>
<td>Fulfilled by:</td>
<td></td>
</tr>
</tbody>
</table>

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Enterprise Accounting

- Complete cash-flow accounting system
- Tracks Revenue, Fixed and Variable Costs, OH
- Provides direct measure of effectiveness of simulated enterprise

### Revenue

<table>
<thead>
<tr>
<th>Round</th>
<th>(A) Total Shipped Aircraft</th>
<th>(B) Price Received aircraft</th>
<th>(C) Total revenue = A x B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>450</td>
<td>900</td>
</tr>
<tr>
<td>2</td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>450</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>350</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>350</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Costs

<table>
<thead>
<tr>
<th>(D) Total of purchased parts invoices</th>
<th>(E) Total Inventory (parts - all facilities)</th>
<th>(F) Carrying Costs (all facilities)</th>
<th>(G) Capital Improvements (all facilities)</th>
<th>(H) Engineering Overhead</th>
<th>(I) Total Costs = D+E+F+G+H</th>
<th>Net Profit = C - I</th>
<th>Cumulative Profit = sum(Net Profit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380</td>
<td>55</td>
<td>540</td>
<td>0</td>
<td>200</td>
<td>1175</td>
<td>-275</td>
<td>-275</td>
</tr>
</tbody>
</table>

**BOTTOM LINE!**
Use of Simulation

• One day (about 2/3s of the teaching time) dedicated to simulation
• Simulation played in 12 minute active rounds, interspersed with time for reflection, planning, and analysis
• Round 1-2: Learn and Baseline
• Round 3-4: Process Improvements
• Round 5: Enterprise Lean
## Process Improvements

<table>
<thead>
<tr>
<th>Simulation Improvements</th>
<th>Lean Principles</th>
<th>Typical Student Actions</th>
</tr>
</thead>
<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 between Facilities – this requires an “engineering request” (approved by instructor)</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) facilities – this requires “corporate approval” (also by instructor)</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 by eliminating paperwork – requires “corporate approval”</td>
<td>Eliminate Unnecessary Tasks, Standard work</td>
<td>Upgrade parts ordering system and standardize orders to single-plane sets</td>
</tr>
</tbody>
</table>

**Students use Lean Process Improvement Tools to make Simulation Process Effective**
Adding Data

Plant A - Tails
7 parts, 60 sec

Supplier Quality Representative

Orders and Parts

Plant B - Fuselage
22 parts, 180 sec

Plant C - Wings
5 parts, 60 sec (two per plane)

Plant D - Final Assembly
3 sub-assemblies, 30 sec

Subassemblies

Manufacturing Table

Customer

Aircraft

Dedicated Supplier

38 parts, 3 orders (+) ?? sec

Suppliers’ Table
Using standard symbols - a simple VSM

Customer

Aircraft

Plant A - Tails
7 parts, 60 sec

Supplier Quality Rep.

Plant B - Fuselage
22 parts, 180 sec

Subassemblies

Supplier
38 parts, 3 orders (+)
?? sec

Plant C - Wings
5 parts, 60 sec
(two per plane)

Plant D - Final
3 subs, 30 sec

Orders and Parts

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Analyzing the VSM

Plant A - Tails
7 parts, 60 sec

NVA Step

Orders and Parts

38
3 ord
?? sec

Lots of paper

Plant B - Fuselage
2 parts,

Too Slow!

18

Subassemblies

Plant C - Wings
5 parts, 60 sec

(two per plane)

Plant D - Final
3 subs, 30 sec

Customer

Aircraft

Simple change rules govern what students can change, and at what cost

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<th>Typical Student Actions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airplane may be redesigned within a constant exterior mold-line</td>
<td>Lean Engineering, DFMA, Supplier Integration</td>
<td>Reduce part count by 10 (to 28 per plane) using large Lego blocks available to suppliers</td>
</tr>
<tr>
<td>Balance Workload between Facilities (again)</td>
<td><em>Takt</em> time, Single-piece Flow</td>
<td>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)</td>
</tr>
<tr>
<td>Change (improve, eliminate, or move) Facilities</td>
<td><em>Takt</em> time, Single-piece Flow</td>
<td>Students find they must increase capacity at some manufacturing plants (but can now justify it economically)</td>
</tr>
<tr>
<td>Further Modernize Supply Chain</td>
<td>Standard work, Just-in-Time, <em>Kanban</em></td>
<td>Implement a two-bin <em>Kanban</em> inventory management system throughout enterprise</td>
</tr>
</tbody>
</table>

**Students use Lean Enterprise Tools to make Simulation Process Outstanding**
Key: Redesign Airplane

Practice Lean Engineering:
• Cut part count
• Reduce part types
• Fix weak tail
• Easy to assemble
• Obeys constraint of unchanged moldline
Example learning by doing: Kanban System

- Implement pull inventory and production control system
- Learn complex, context-dependent tool through simulated experience

Full Kanban bin cues transport

Empty receiving cues emptying Kanban bin

Empty Kanban bin cues order fulfillment

Empty Kanban bin cues transport
Results

Students get simulated experience of process improvement

lean.mit.edu/ednet

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Simulation-Based Learning and our Learning Objectives

- Increased comprehension of the curriculum
  - Controlled studies show increased comprehension using “games” vs. lectures or static web-based learning
  - Controlled studies also show improved outcomes measured by behavior
- Better understanding of context and holistic, system-spanning nature of lean changes
- Learning through experience - a practice field for lean change
  - Supported as goals, improved outcomes unproven
- Increase student involvement and excitement
  - Observed!

Most literature on computer-based simulations
Non-computer Peer Efforts

- **Simple simulation to make one learning point**
  - Beer game
  - Dot games
  - Dice games

- **Lean Manufacturing Simulations**
  - Timewise clock manufacturing
  - Various lego games - cars, etc.
  - Lean Shipbuilding

- **Design and Analysis Simulations**
  - Requirements and concept design
  - Engineering processes

*Mostly simple systems designed to teach specific lessons*
CDIO and Continuous Process Improvement

- Typical Continuous Process Improvement methods have structures very similar to CDIO!
  - Plan-Do-Check-Act (PDCA)
    - Shewhart, Deming
  - Define-Measure-Analyze-Improve-Control (DMAIC)
    - Six-Sigma
  - Mobilization-Diagnosis-Redesign-Transition
    - Hammer (Re-Engineering)

- CPI is about designing and operating business systems!

- We avoid favoring any one camp

Course CONTENT resembles CDIO
• Course methods puts students through a CDIO cycle *in the simulated world*
  • *Comprehend*: the existing system and its weaknesses, using lean tools and quantitative data found in the simulation
  • *Design*: the new system, using standard design techniques, and constrained by the “physics” and finances of the simulation
  • *Implement*: the new system; facing practical challenges (mostly organizational) above and beyond the design
  • *Operate (and Iterate)*: keep the new system working, face new practical challenges and start the process over again to take it to the next level

Course METHOD is CDIO
Simulations allow CDIO on complex systems

- Most complex systems are not available for students to manipulate for teaching purposes
- Students can get a CDIO experience from manipulating a simulation if:
  - Complex enough to capture the key features of the emergent behavior of the system
  - Simple enough to have an acceptable learning curve
  - Fast enough to allow multiple change cycles within teaching period
  - Credible and Fun

Simulation ENABLES CDIO
Evaluation

- Students asked if Lean Academy Modules “provided positive reinforcement of the concepts”
- Six academies, N=194
- Circle = 90% confidence
- Bars = extremes between means within categories

Simulation assessed significantly higher than other types of learning in ALL cases
Comments Indicate Simulation Goals Met

• Increased comprehension of the curriculum
  … helped with application of what we learned in lecture
  It took a while to get the concepts but it finally clicked during the 2\textsuperscript{nd} segment [of the simulation]

• Learning through experience - a practice field for lean change
  \textit{Hands on – Excellent. Telling someone how something works is fine. Having someone do it teaches it}
  \textit{LOVED the simulations. Figuring stuff out yourself makes things make much more sense}

• Increase student involvement and excitement
  \textit{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.

• Team Building
  \textit{Created a good sense of camaraderie}
Comment Categories

- Types of answers to open question “what did we do well today”
- 106 responses (out of 182) mentioned simulation
- Responses binned by category

Simulation well liked
Comments reflect learning objectives
Caveats

- Evaluation based on satisfaction, not outcomes
  - Outcome data for Lean Academy positive, but does not differentiate between modules
- Cost and Time
  - Significant upfront expense (Legos, etc.)
  - Need 6 trained facilitators
- Simulations are vulnerable to disruption
  - Logistic and facilitation errors degrade experience
- Cannot satisfy all learning styles
  - Students asked for more and less simulation time
  - Real stress from simulated process difficulties, competition

Typical issues for teaching simulations
Conclusions

• Unique simulation of an aerospace enterprise created
  • Subset used in Lean Academy
  • Teaches use of lean process improvement tools
  • Gives context and hands-on experience
  • Increases student involvement and enthusiasm

• Simulation provides a laboratory for CDIO of complex systems
  • CDIO teaching methods well aligned with material
  • Process improvement techniques have CDIO structure!

• Feedback indicates simulation is successful
• Caveats typical of learning simulations in general

A CDIO Success Story