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Lean Engineering: Doing the Right Thing Right

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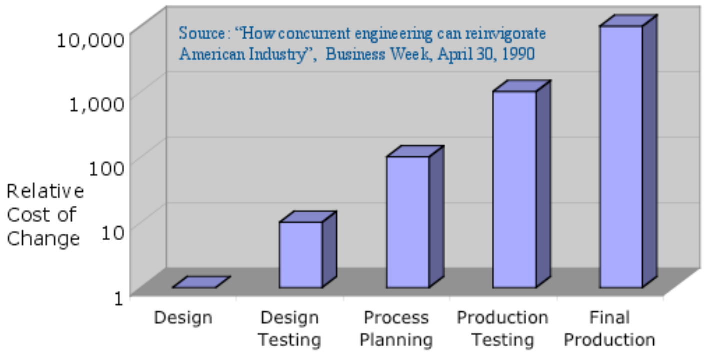
Lean techniques are having a major impact on aerospace manufacturing. However, the cost and value of aerospace (and many other) products is determined primarily in product development. Migrating lean to engineering processes is ongoing in the industry, and a subject of study at the MIT Lean Aerospace Initiative. This paper summarizes findings to date, with references to both research literature and successful implementation examples. To implement lean engineering, a three-part approach is needed: *Creating the right products, with effective lifecycle and enterprise integration, using efficient engineering processes*.

I. Introduction

A. Need and Challenge

The impact of the Lean movement on manufacturing processes has been, depending on the industry, anywhere from strong to revolutionary. In aerospace, lean has made a strong contribution to improving manufacturing efficiency. However, if lean improvements are confined to manufacturing, they will represent only islands of success in a sea of inefficiency. The recent book from MIT's Lean Aerospace Institute, *Lean Enterprise Value*,[1] has pointed out that improvements in manufacturing alone will make only a marginal difference in the ultimate system costs. The entire enterprise must undergo a lean transformation for the impact to be significant, and ***the key is engineering***. Although engineering's contribution to lifecycle costs can be modest, much of both the eventual lifecycle cost, and the eventual user satisfaction, are determined by engineering. It is well known that about 80% of the product's lifecycle costs are determined by the end of detailed design.[2] The key to affordable products is effective engineering.



Source: "How concurrent engineering can reinvigorate American Industry", Business Week, April 30, 1990

Figure 1. Relative costs of a design change.

Figure 1 shows, notionally, the relative cost of a design change at various stages in the lifecycle process. It is much easier to get things right during design than to fix engineering's mistakes later. More subjectively, but more importantly, the users' satisfaction with the value produced by the product is also largely determined by the design of the product. Production and service of a quality product, usually seen as the "delivered value," are not valuable if the product itself does not please the customer.

B. Approach

Application of lean techniques to product development processes is underway across the US aerospace industry. However, the techniques are not well established, and many practitioners are essentially feeling their way forward,

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learning by doing, and seeing what works and what does not. Over the last five years, academic and industry groups, most notably the product development community within the Lean Aerospace Initiative, have shared the insights gained in this collective effort, and reached a rough consensus on what lean means in the product development context. The term used for these efforts by most industry members, and hence adopted here, is *lean engineering*.

Lean engineering has three goals, representing three very different areas of process improvement. They are:

- ***Creating the right products…***Creating product architectures, families, and designs that increase value for all enterprise stakeholders.
- ***With effective lifecycle and enterprise integration…***Using lean engineering to create value throughout the product lifecycle and the enterprise.
- ***Using efficient engineering processes…***Applying lean thinking to eliminate wastes and improve cycle time and quality in engineering

In this paper we will present the current state of the art in these three areas of lean engineering. The results of applying lean engineering in practice will be discussed in a results section, and the paper will conclude with a summary of the work yet to do before lean engineering becomes the norm in the aerospace industry.

II. Creating the right products

A. Best Practices

At the beginning of concept development, the engineer encounters evolving user preferences, imprecise specifications of product parameters, varying levels of technology maturity, market and funding uncertainties, and perhaps evolving regulatory, political and other hard-to-quantify factors. Often called "the fuzzy front end" of product development, this phase is absolutely critical to embarking on a lean engineering undertaking. Several key best practices have emerged.

Perhaps the most important element is to focus on understanding the customer and end user value expectations for the product – its features and attributes, quality, price or cost and availability. No amount of efficient lifecycle engineering or engineering process improvement can make up for a poorly conceived product that a customer does not want. Difficulties include less-than-fully-defined user value (after all, the product is less than fully defined at the beginning of product development) and the importance of multiple stakeholders, particularly when end user and acquirer (stakeholder that puts up development money) may be different. The issue of value definition and creation in product development was studied by Slack.[3] How aspects of value can be systematically considered, and how the interaction of multiple early stakeholders can be handled, are also addressed by Slack. Figure 2 shows customer (acquirer) value considerations, including product quality and functionality, schedule, and price. Slack advocates similar breakdowns of the aspects of value for all stakeholders, and informed negotiations of goals for product development that will maximize value for as many stakeholders as possible.

A second important element is to keep the "design space" as open as long as possible before making critical decisions to address uncertainty. Toyota uses a technique called set based design,[4] in which the design choices for subsystems and components are made from a set of possible choices ranging from a proven design to ones from emerging technologies. The final choice is delayed as long as possible, even into the detail design stage, in order to have the best information available before a final choice is made. Bernstein[5] found little evidence of set based thinking in aerospace, noting an opposite trend of making early decisions on product architectures and features. Currently there is research underway to use real options approaches and other uncertainly management strategies to address this challenge in aerospace, but there is little evidence of their use in actual programs.

A third important element is to choose products and architectures which may be upgraded or improved in future product offerings. Block upgrades, stretched or shorten airframes, improved engines, and other derivates of the initial design are all good lean engineering approaches to reducing cost and development time of future products, while providing improved product features,

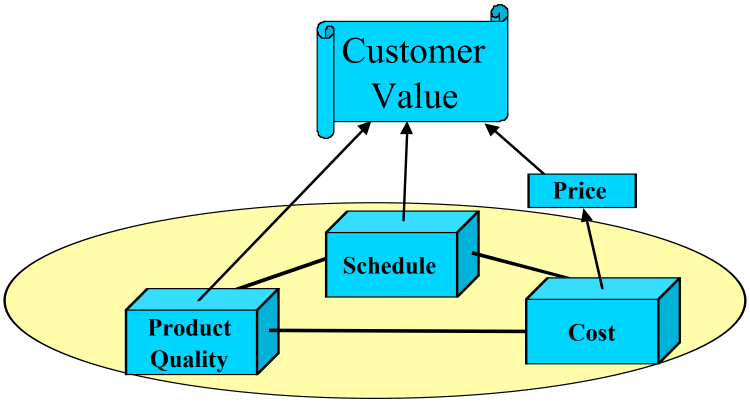

Figure 2. Customer value framework according to Slack.

attributes and quality. Generally "point designs" (highly optimized and specialized solutions to specific problems) are not good lean engineering candidates.

A related issue is removing high-risk technology from the critical path of product development. Use of technology demonstrators or other similar approaches can remove the risk of unplanned delays during which resources can be wasted and the product can miss the market opportunity.

B. Framework for Effective Front-End Processes

A general framework for an effective "fuzzy front end" product development process was developed by Wirthlin and Rebentisch,[6,7] based upon a literature review and studying 9 military and 8 commercial organizations. One focus of their study was to determine how successful organizations make decisions to proceed with developing a particular product from amongst a choice of many product opportunities; i.e. product portfolio management. Their framework consists four stages with identified best practices:

1. Identification of Requirements:
    - Best-in-class use small teams with multi-disciplinary backgrounds
    - Process adequately funded
    - Multiple requirements identification methods used (e.g QFD, Pugh analysis)
    - Independent assessment of solution
2. Initial Screening:
    - Senior-level team decides which projects proceed with follow-on funding (and which do not)
    - Active portfolio management
    - Strategic plan, doctrine, or product strategy and resource constraints used as a guide in prioritization
3. Concept Development:
    - Requirements expressed as variables within a desired range that can be tested and validated
    - Team remains intact during this process to preserve organizational memory
    - Data generated through prototypes/ simulation for tradeoff analysis
4. Business Case Development:
    - Clear and concise product concept, architecture, and concept of employment
    - Based on product, technology evolution/insertion, and product replacement strategies; fit with portfolio; returns to organization

Organizational enablers include roles and responsibilities of management and integrated product teams, and employee skill development and training. Business enablers include such things as coupling to research and development investments, information technology infrastructure, and commitment or resources.

Wirthlin and Rebentisch also developed an assessment model to measure an organization's capability to execute the processes embodies in their framework, and applied the model to the 17 organizations they studied. One finding from the study is that best in class organizations score high on most elements in the framework, indicating a holistic approach is needed for an effective concept development phase.

C. Example Tools: MATE and ICE

The Wirthlin-Rebentisch framework can serve as an overall guide to the first phase of lean engineering, but specific tools or techniques are needed to execute the various stages. Multi-Attribute Tradespace Exploration (MATE)[8,9,10] is one example. It has been developed and applied in the space systems domain for the system-level design stage. Its intent is to allow informed upfront decisions and planning, so that the detailed design process which follows is aimed at the right solution, and is forewarned of potential problems and forearmed to seize potential opportunities.

MATE is a model-based high-level assessment of many possible solutions to the problem to be considered. The key purpose of this step is to avoid premature concentration on a point solution. MATE gives the early decision makers a basis to explore a large number of solutions and their adaptability to changes. It allows this through the quantitative consideration of many aspects of uncertainty, including environmental or user needs changes, technical developments, policy changes, and market instability. It also provides a quantitative way of assessing potential capabilities (of, for example, proposed or hoped-for new technologies) through the use of what-if scenarios. MATE has been used on several projects to date, and is part of a movement towards understanding trades spaces and design options in conceptual design. Figure 3 shows the conceptual flow of the MATE process.

Once an architecture has been selected from the MATE tradespace, rapid development of a design or set of vehicle designs is done using Integrated Concurrent Engineering (ICE). ICE and similar methods for rapid design are under development at a variety of industry and academic settings. An interdisciplinary team with tools that communicate seamlessly through a common database does design *sessions* in physical or at least virtual co-location. ICE design sessions typically last several hours and usually address one major trade per design session. Team members work together, iterating very rapidly towards an improved design. Design changes are tried until a design is found that satisfies all major requirements.

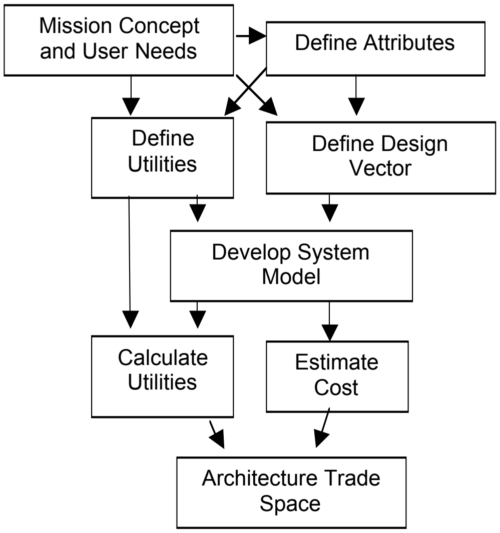

Figure 3. High level description of MATE.

MATE and ICE utilize a key lean practice of "seamless information flow." By allowing rapid trade space studies followed by detailed evaluation of candidate architectures, wasteful waiting time is eliminated from the concept development phase, thereby allowing more rapid product development cycle times. They also allow for taking into account market and technology uncertainty in the resulting product architecture.

D. Continuing Use of Front-End Tools

To close the discussion of creating the right products, it should be noted that the best practices should continue into system-level and detailed design. Dare, et al.[11] studied eight software intensive system designs to ascertain effective methods for the system developer to interact with the customer and end user during the design phase. They found that effective use of a "system representation" such as a computer model, prototype, or modified existing system greatly facilitated communication and design adaptation to better meet the customer and end user needs. It is simply not possible for requirement documents to capture all the details needed to specify what the end user wants. Continual involvement of users throughout the design process contributes to creating the right products. Users should be included on Integrated Product Teams, Virtual Reality Reviews, and other elements of a lean engineering process.

III. Product Lifecycle and Enterprise Integration

A. Product Development's Role in The Value Chain

The product value chain in Figure 4 depicts the role of key stakeholders in delivering the expected value. The value chain is the set of all the stakeholders that are linked together in the value stream. In a lean enterprise, the customer specifies value and companies must deliver products that have sufficient features to justify their price. During product development engineers must design products that are producible and meet the customer's value expectations for price, performance, quality, and schedule.

To accomplish this, engineering needs to work closely with all stakeholders. In today's industry, this is done with Integrated Product Teams (IPT's) which can also include suppliers, the customer, production, and relevant engineering disciplines. Since 60-80% of the product (by value) is outsourced to suppliers, experience shows they should be involved early in the product development phase.[12] Suppliers have considerable knowledge and experience to bring to the table to contribute to a producible design that meets customer value expectations. In many cases, the prime contractor will not have the expertise to specify the design of subsystems and components contributed by the supplier. Production is where the value is created that is eventually delivered to the customer. In a lean enterprise, suppliers are treated as partners, with information being openly and seamless shared between the prime and their suppliers. The prime will invest resources to help their suppliers become lean, and both parties will benefit from this investment.

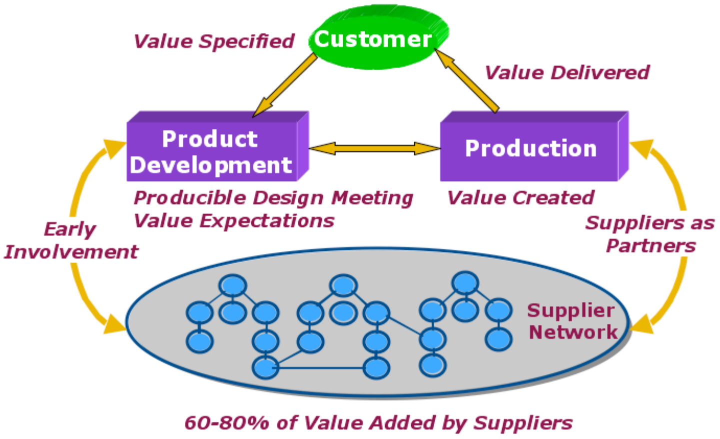

Figure 4. Product Value Chain.

B. Role of Systems Engineering

Systems Engineering is the process used to develop the top-level architecture of the product and then flow-down the mandatory/implied customer requirements to a set of detailed specifications from which the final design is evolved. Aerospace products are complex and engineering must simultaneously be designing for the required product performance, reliability, maintainability, unit cost, life cycle cost, and supportability that the customer specified or is implicit in a well-engineered product. Designing for so many requirements at the same time is often referred to as "designing for X."

Efficiently handling all these requirements and not letting any of them "fall through the cracks" is a difficult job, requiring an experienced systems engineering staff well-versed in requirements flow-down, conducting trade-studies, product performance analyses, configuration management, data management, and capable of independent analyses of reliability, maintainability, human factors, supportablity, and life-cycle costing. Systems engineering processes are well established,[13] although not always fully carried out. Carrying out good systems engineering is a necessary component of integrating lean engineering in the product value stream.

C. Lean Engineering Tools for Integrating the Value Stream

The "tool box" for doing engineering in such a way that lean is enabled through the enterprise includes:[14]

- Design for Manufacturing and Assembly (DFMA)
- Solids Based Design
- Common Parts / Specifications / Design Re-use (hardware and software)
- Variability Reduction / Dimensional Management
- Production Simulation

Each of these tools will be briefly discussed in the following paragraphs.

1. Design for Manufacturing and Assembly (DFMA):

There is a great deal of work ongoing in the area of design for manufacturing. Often, simply reducing part count is the key. Reducing the parts in the design helps reduce recurring and non-recurring cost. A part not on the aircraft does not have to be designed, tooled, N/C Programmed, manufactured, assembled, inspected. It never is re-worked or scrapped. It is never in inventory so it has no production control costs and it doesn't weigh anything. In addition, the customer does not have to provide spare parts for it. The engineer's job is simple: give manufacturing and supplier management fewer parts in the design, designed with high quality so they fit the first time, and made with manufacturing processes that are robust/repeatable and provide a high yield. This is simple to say, hard to execute, but will provide a design that can be built efficiently and meet target cost.

As an example, the F/A-18E/F is a major derivative of the successful F/A-18C/D. During the design of the E/F, Boeing engineers used DFMA to significantly reduce the number of parts in the design, e.g. in the Forward Fuselage, the C/D had 5907 parts, the E/F had only 3296 parts, a reduction of 2611 parts. Similarly, the wings & horizontal tail, and the Center/Aft Fuselage parts count were reduced so that in total, 14,104 parts on the C/D were reduced to 8099 parts on the E/F models. This is a remarkable achievement since the E/F aircraft is 25% larger than the original F18.

2. Solid-Model-Based Design

Figure 5 shows a typical advanced suite of integrated computer-aided design tools that utilize parametric solid models as a basis. These models are seamlessly transferred to supporting software routines, e.g. Smart Fastener determines rivet spacing and grip-length; Part Surfacer provides the cutting path for the CNC milling machines; PACKs is a parametric knowledge based system for detail designing composite structures. All of the detail-designed parts are fed into a total Assembly Model or "electronic mock-up." Daily "virtual reality" design reviews are held among collaborating design locations all looking at the 3 dimensional solid model of the parts and assembly. Suppliers also feed their 3-D design models into this electronic assembly model for review and integration. The total Integrated Product Team can participate in the input and review of the emerging design. First article defects are significantly reduced and total design cycle time is shortened. Such models, in addition to their many engineering virtues, enhance communication across the team and serve as "system representation" for interdisciplinary communication, as referenced earlier in the study by Dare, et al.

3. Common Parts / Specifications / Design Re-use:

Parts commonality makes sense at all levels. In particular, having the same components at the level of the aircraft, missile, helicopter or other product that is "field replaceable" for maintenance allows us to capture not only non-recurring cost savings (design, tooling, fabrication, parts control) but operations and support costs savings in reduced maintenance costs, reduced spares procurement costs, and reduced training costs for the life of the aircraft.

One trick in reducing the number of parts is to use "common" or "multi-use" parts. Utilizing symmetrical parts instead of "left-handed" and "right-handed" parts (e.g. parts for the left wing and then *different* parts for the right

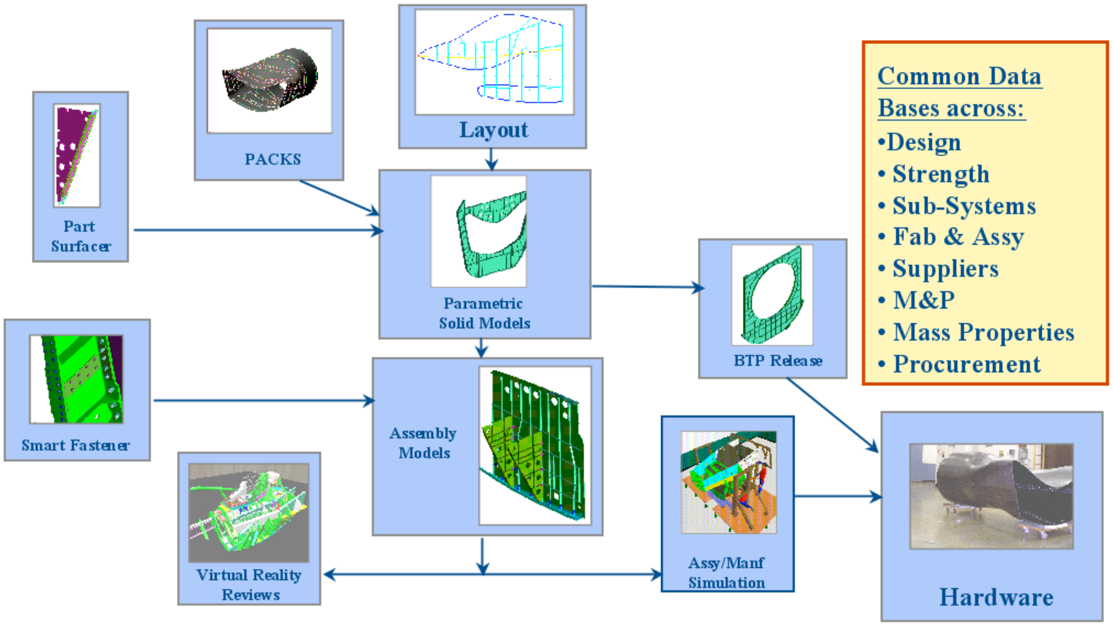

Figure 5. Model-Based Design improves engineering and enhances communication (from Ref. 14)

wing), and using the same design clips, angles and brackets in multiple locations, saves duplicate design, tooling and planning and drives down the cost of manufacturing, parts control, and inventory. The use of parts that are already designed—design re-use—is very efficient from a cost perspective and saves tremendously on cycle time. This same concept of design re-use is also very powerful when applied to the cost-effective development of software but that is beyond the scope of this paper.

There is a huge benefit to airline and military customers when manufacturers utilize common subsystems at the Line Replaceable Unit (LRU) level.[15] Airbus' cockpit controls and displays commonality among the A-320, A-330 and A-340 was described as saving 20-25% in pilot training costs as well as allowing common spare parts inventories for the airlines.

4. *Variability Reduction and Dimensions Management:*

Since the time of Deming and Juran, we know conclusively that variation in design and manufacturing negatively affects product quality. Thus, the science of dimensional management was introduced to guide all aspects of design and proper tolerancing to assure good first-time assembly fit and the reduction of wasteful scrap and rework. Key best practices include engineering use of dimensional management to assure a buildable design, and a linkage to statistical process control during the manufacture of the product. In the overlap region between the two, the emphasis is on the *key characteristics* that control the design interfaces.[16] The objective is to utilize dimensional management tools in the design process to enable manufacturing to be able to put all parts and assemblies into continuous statistical process control for efficient fabrication and assembly operations. Thus, the waste associated with part rejections, re-work and scrap in on-going production will be eliminated from the first part.

5. *Production Simulation:*

With the recent advent of very powerful 3-D software that permits realistic production simulation (e.g. Dassault's CATIA V Delmia) many companies are demanding that the engineers, working closely with manufacturing, tooling, industrial engineering and quality assurance to create a production simulation of the proposed assembly process to improve the entire process and eliminate expensive and wasteful downstream engineering changes in production.

IV. Using efficient engineering processes

A. Inefficiency of existing processes

LAI research and the reports of member companies paint a clear picture of current practice in engineering process. A formal process is required for almost all aerospace engineering activities, to satisfy quality, safety, and regulatory concerns, and to allow management of the complexity of aerospace systems. However, these processes are often poorly defined. They can refer to obsolete practices (e.g., paper drawing when CAD is used), contain detail that is not relevant to most jobs, or miss key practices (e.g., appropriate ways to handle new materials or technologies). They may also capture practices that once were critically important, but have become irrelevant over time—in lean terms, they may be *monuments*.[17] Partly as a result, they are often followed only loosely. Quality work is nevertheless accomplished, thanks to the professionalism of the engineers and managers involved, and conservative review and verification practices. This situation has, however, a high potential for process inefficiency.

Not surprisingly, this inefficiency is observed. Figure 6a shows typical survey results.[18] Engineers were asked to assess how much of their effort (in time-card hours) was spent adding value directly to the tasks at hand, how much time was spent in necessary support tasks, such as set up, and how much of their time was wasted. Forty percent of their effort was described as pure waste, and only thirty percent value added. Limited formal study[19] data confirms that 30%–40% of engineering effort is typically wasted. Much worse, from a lean point of view, is the data collected on work packages shown in Figure 6b. When engineering work packages were tracked (as opposed to engineers), they were found to be inactive 60% of the time![20] No effort was being expended on them and hence, by some measures, they were not costing anything. But assuming the work packages have some value and level of urgency, it is clearly a waste that their cycle time is more than doubled simply because they spend a lot of time sitting on desks and not being worked on. Notionally combining these data yields an alarming picture. A typical work package is undergoing value-adding activity only 12 percent of the time! Conversely, 78 percent of the time it is in a state of pure waste—either idle or undergoing useless processing.

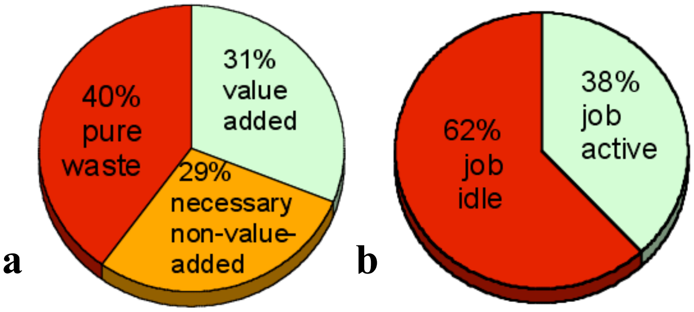

Figure 6 a) value assessment of charged hours, b) activity on work package

This alarming picture is difficult to accept at first, but is confirmed by multiple independent sources. Anecdotally, but very consistently, LAI member *kaizen* process improvement events reveal 75%–90% job idle times in the "bottleneck" processes selected for improvement.[21] A simulation used in LAI seminars[22] produces similar results. The cumulative picture from these sources is that one can *expect* to find 60%–90% time waste in a typical engineering process, even if all of the steps are value added. This level of waste exists even if all of the personnel involved are busy all of the time, and the majority (60% in Figure 6a) of their time is spent on value added or at least enabling activities.

B. Applying Lean to Product Development processes

Engineering processes differ in fundamental ways from factory processes. Most of the differences are driven by the fundamental *uncertainty* of product development processes—at the beginning of the process, the exact content of the output is not known. This is in stark contrast to factory operations, where the ideal is to make a part precisely the same as the last one. The product development process is also acting upon *information* more than physical material—the ultimate output is the specification of a product rather than the product itself. Finally, most product development processes are acting on a mix of jobs, of greater or lesser difficulty or complication. This is not a fundamental difference; it is analogous to a factory working on *mixed-model production*. It does, however, complicate the application of process improvements.

We find we must re-imagine how the basic concepts of Lean Thinking—value, value stream, flow, and pull—apply. This re-imagining is experience based; a summary of LAI member experience is given in Table 1. Value, especially as the process is underway, is harder to see, and the definition of value-added is more complex. The value stream consists of information and knowledge, not the easy-to-track material flows of the factory. Due to uncertainties or interdependencies (e.g., between different analytical steps), branching or iterative flows may be beneficial, which is rarely if ever true in the factory. The "pull" to which the system should respond is also rarely a simple customer demand that can be used to calculate a *takt* time (a metronome-like beat that paces the process; at each beat a product is created). Product development operations are usually intermediate steps in an overall enterprise effort to create value. Finally, perfection is even harder to reach, as simply doing the process very fast and perfectly with minimal resource used is *not* the final goal; efficient product development process is simply an enabler of better enterprise performance and better products.

Table 1. Applying the five lean steps to Engineering

	Manufacturing	Engineering
Value	Visible at each step, defined goal	Harder to see, emergent goals
Value Stream	Parts and material	Information and knowledge
Flow	Iterations are waste	Planned iterations must be efficient
Pull	Driven by takt time	Driven by needs of enterprise
Perfection	Process repeatable without errors	Process enables enterprise improvement

To apply lean improvement techniques to product development processes, LAI has developed the Product Development Value Stream Mapping (PDVSM) method.[23] The PDVSM is based on years of LAI research in lean product development. Academic research and member experience and best practices are used to translate, adapt, and expand value stream mapping concepts to the unique needs of product development processes. The aim of using the PDVSM or other lean techniques is to make the basic processes of product development as efficient as possible. This not only saves resources; it more importantly can drastically reduce cycle time, and free resources to do the important jobs of designing the right product and integrating with the lean enterprise described previously.

V. Results

Here, we briefly review some results of applying the lean engineering techniques described above to actual aerospace programs. These examples are representative, designed to illustrate the potential of lean engineering, rather than exhaustive; further results are given in the references.

A. Selecting the right product

Figure 7 shows the results of a MATE analysis of potential space vehicles that will assist satellites and other vehicles with orbital transfer maneuvers—Space Tugs. The trade space of possible space tugs was explored. The potential users desires for complexity of grappling equipment, delta-V (ability to change orbits) and speed were used to rank vehicles designed with various combinations of grappling equipment, fuel load and type, and propulsion type. The results show that existing designs, (which have failed to go into production) were non-optimal. The Pareto front (the designs with maximum performance for a given cost) is occupied by low-capacity, low delta-V vehicles which might be useful for tending satellites in similar earth orbits (the Tenders), electric propulsion vehicles which are slow but have very high potential delta-V capabilities and are cheap (the electric cruisers), and high capability, fast, high delta-V vehicles that require nuclear thermal propulsion (the monsters). It was recommended that future work in this area be concentrated on these classes of vehicles.

Figure 7 also shows an ICE development of an Electric Cruiser vehicle, which fleshes out this concept, provides confidence in its feasibility, and identifies issue (such as durability of the thrusters) for further study. The ICE work done in this case took only about a month from start to finish. Individual vehicle designs could be explored in under four hours once the ICE analysis modules were created and integrated.

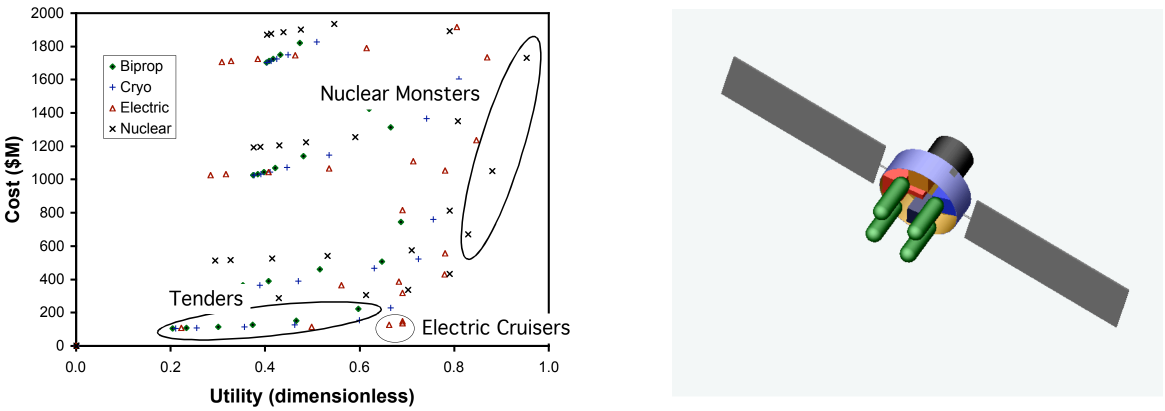

Figure 7. MATE analysis of the trade space for space tugs and ICE development of a design (from Ref. 9).

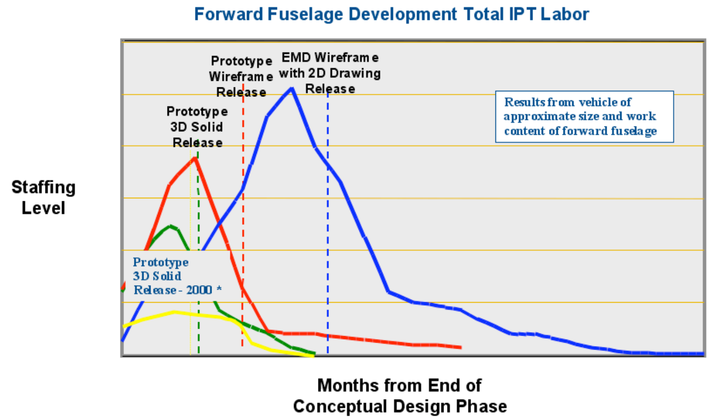

Figure 8. Results of lean integration tools on aircraft structure development (from Ref. 24).

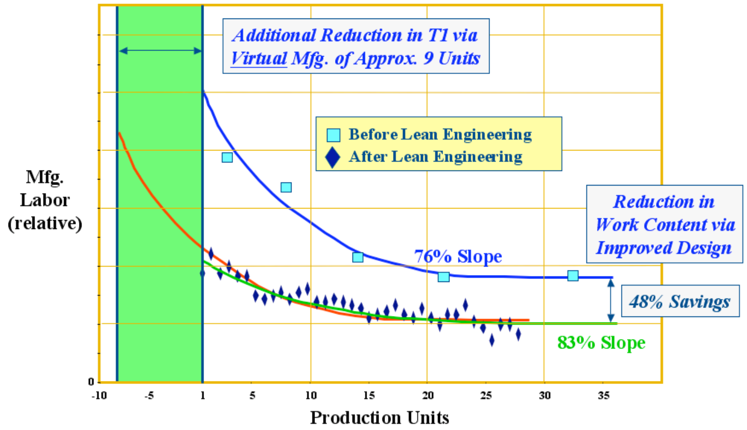

Figure 9. Production labor before and after lean engineering (from Ref. 14).

B. Integrating the enterprise

Using lean tools to integrate the engineering process into the product lifecycle has had dramatic results. Fig. 8 illustrates the impact of lean engineering on labor and cycle time for development of four generations of comparable forward fuselage configurations. Results show a reduction of approximately 50% in cycle time and 80% in maximum staffing levels. We believe these results to be the product of changes in knowledge management and transfer, process changes enabled by the application of 3D solid geometry.[24]

Figure 9 shows the effects of the same tools on the manufacturing labor as a function of unit number, again for forward fuselages. Two comparable products are shown, one developed using the lean tools, and one without. The manufacturing labor content is show as a function of the unit number. The lean techniques not only reduce the stable work content by 48%, they also have a dramatic effect on the learning curve. The virtual experience gained using manufacturing simulation was the equivalent of 9 units of actual production. The *first* unit produced after lean engineering had labor content only slightly above the long-term stable level.

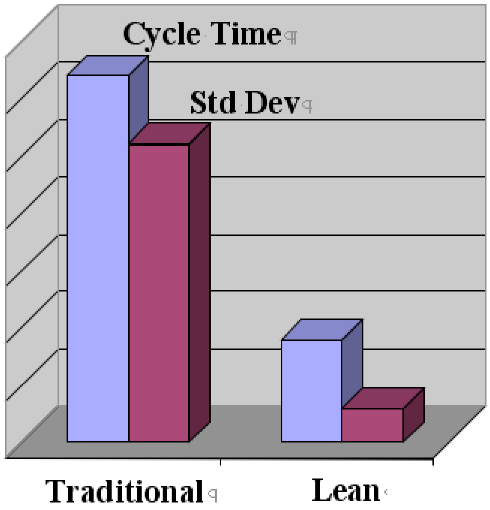

Figure 10. Results of applying lean to engineering processes (adapted from Ref. 23).

C. Efficient Process

Figure 10 shows a typical result from the application of lean techniques to a product development process. The process (in this case, drawing release) was plagued by very long, and extremely variable, cycle times. By mapping the value steam, and using lean techniques such as work cells and single piece flow, average cycle time was drastically reduced. More importantly, so was the variation in cycle time. With a short, predictable cycle time, the release of drawings could be scheduled with confidence, enabling the application of lean to other processes dependent on the drawings. As an additional benefit, it was found that the standardized process also drastically reduced drawing errors, without any additional work or inspection.

VI. Looking Forward

We have reviewed the application of lean techniques to engineering. Engineering requires techniques not only for an efficient process, but also for selection of the right product (so value is in fact created) and for the enabling of lean throughout the product value stream (so that all processes in the stream can be lean). The results section shows dramatic examples of the effect this can have on the selection of designs, and on the efficiency of both the engineering process itself and the downstream processes such as manufacturing.

Unfinished to date are techniques to integrate these approaches so that a set of tools can be used to do it all—pick the best product, design it efficiently and quickly, and assure that the design can be built, used, serviced and updated in a lean way. This is the vision of perfection that is driving ongoing progress in Lean Engineering.

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