The preceding description of lean manufacturing and its potential for cost savings provides some insight into the complexity of the system. Further complexities arise when lean manufacturing results (either actual or predicted using pilot programs and initiatives) must be somehow incorporated into formal cost analysis. Some of the challenges cost analysts face are estimating costs and savings when efforts in one particular cost category have results that flow through other cost categories, assessing the effects of lean on historical cost improvement curves, deciding what adjustments are required to incorporate lean into historical CERs, and judging how DoD and the USAF should give credit (i.e., reduce estimated costs) for lean implementation. In this chapter, we discuss these specific issues.

INTEGRATION ACROSS AREAS

Lean manufacturing requires significant shifts in practices throughout the plant, and changes in one particular area may affect costs across different functions. For example, a focus on quality involves up-front design attention to manufacturability; manufacturing processes focused on first-time quality, using such tools as cellular production, visual controls, shadowbox tool storage, and so forth; low inventories to make quality problems immediately obvious; attention to supplier quality processes and willingness to form partnerships with suppliers on quality improvements; and a highly trained, flexible workforce that can perform self inspections. Hence, efforts to improve quality will affect multiple functions in the plant. Lean
organizations need to make efforts to tightly couple processes throughout the plant because of these spillovers. Cost-benefit studies of new processes should capture costs and improvements in all areas. However, the very great majority of the lean savings data that plants presented focused on one area (primarily because of the scope of the pilots) with little description of how it would flow to other cost categories. Using traditional cost estimating methodologies, government and industry estimators often assume that lean initiatives that reduce direct manufacturing labor hours will also reduce support hours, overhead, and G&A costs by using fully burdened wrap rates to cost out savings. These assumptions may not reflect actual outcomes when pilots are scaled up across the enterprise, however.

CCDR regulations require companies to collect cost data by lot in particular categories, which broadly are design and development, tooling, quality assurance, direct manufacturing, purchased materials, and overhead and administrative costs. To some extent, this forces attention on costs and benefits of investments in new tools and processes according to these categories. However, as discussed many times in this report, a critical insight of lean is that activities in these different categories can be closely interrelated. Table 11.1 lays out some of the activities that occur in each CCDR category in a lean environment and the interrelationship of each with the others.

It is not the goal of this report to create a checklist of requirements for lean in defense aircraft production, and the preceding table is by no means sufficiently complete to be such a list. Instead, the table can be used by government analysts as a broad tool to address the linkages between the different functions in the organization and to understand how specific lean initiatives may have ripple effects outside their immediate cost category.

LEARNING CURVES, STANDARD HOURS, AND MATERIAL IMPROVEMENT CURVES

A brief, somewhat simplistic review of how a cost estimate is developed for an aircraft will help illuminate the problem facing analysts in how to incorporate lean into their cost estimates.1

1See Lee (1997) for a complete explanation of learning curve theory.
Table 11.1

Exemplar Interrelationships of CCDR Categories

**Engineering:** Incorporate input from all parties to ensure design is manufacturable, yet meets customer’s operational needs and support requirements. Cross-functional teams allow up-front communication of many issues.

- Tooling: When designing tooling, incorporate lean design principles. Minimize set up times. Flexible, reusable, low-cost tooling. Data from design stage can be used as input into CNC machine tools.
- QA: “Design quality in”—pay attention to quality issues in up-front design.
- Manufacturing: Ensure manufacturability up front by considering how parts fit together, unitization, and ergonomics of workers. Ensure DFM/A.
- Purchased materials: Incorporate key suppliers’ perspectives in initial design phase to improve design with their expertise and ensure manufacturability of subcomponents up front. Closer link with suppliers to reduce risk of larger, higher-value parts. Easier to manage smaller number of parts in inventory. Fewer suppliers due to fewer parts.
- Support/Overhead Functions: New computer tools change ratio of engineering direct labor to overhead investment in new techniques.

**Tooling:** Model 3-D solids (CATIA, UNIGRAPHICS). Computers link distantly located engineers, participants on IPTs; up-front concern with part count reduction; fewer tools to design; low inventory requires well-maintained machines.

- QA: Properly designed tooling and tooling concepts can help minimize quality flaws in manufacturing process; attention to ergonomics of tooling reduces damage caused by workers in constricted areas.
- Manufacturing: Flexible tool philosophy; reduction in setup times; HSM allows for unitization, cuts labor cost. Virtual factory models processes to ensure mechanics/machines can physically do work; worker maintenance of tools; computerized work instructions so workers can quickly access instructions.
- Purchased materials: Close relationships with tooling suppliers to minimize costs and maximize tooling technology.
- Support/Overhead Functions: Attention to overhead costs in trade-offs between tooling investment and additional workers; reduced tool inventory reduces overhead costs.

**Quality Assurance:** Quality data for SPC can be collected, assessed digitally.

- Manufacturing: Emphasis on Six Sigma quality; SPC; 6Ss (housekeeping plus safety). Without inventory, first-time quality becomes more critical as manufacturing cells lose buffers.
- Purchased materials: First-time quality from suppliers reduces need for excess inventory; certification of production processes at suppliers; costs of inspection and returns reduced.
- Support/Overhead Functions: Set up quality monitoring/auditing function; establish training program for worker self-inspection; reduced QA requirement in receiving function.
Table 11.1—continued

**Direct Manufacturing:** Pull, single-piece manufacturing; flexible, well-trained employees can perform tasks well, also do simple repairs, assess quality problems, make suggestions for improvements; train workers on quality, SPC techniques; work on quality problems, etc.; easier to manufacture items with fewer parts.

- Purchased materials: Suppliers help keep inventory down by delivering parts where needed and only when needed (JIT).
- Support/Overhead Functions: Production rationalized so less space on factory floor needed; attention paid to overhead or reductions in direct labor means fewer workers may carry same burden of overhead with increased wrap rates.

**Purchased Materials:** Best commercial suppliers focus cost reductions and performance improvements. EDI with suppliers—computerized ordering, payment; inventory receiving and management uses bar codes with information sent automatically to manufacturing; automatic payment of suppliers; effective ERP/MRP in place.

- Support/Overhead Functions: Materials handling activities reduced through many initiatives, reducing material burden rate.

Because purchased material, parts, and subassemblies constitute the majority of the value-added costs of an aircraft at the prime, for a production estimate, a list of all purchased materials is compiled (the bill of materials) and prices paid previously for each item (if available) are obtained. After multiplying each of these out for the aircraft, the purchased material is reduced lot by lot in the estimate based on a materials improvement curve. These curves have historical validity as the actual costs of these materials may be reduced by 3–5 percent from the previous lot (probably in part because of learning curves at the subcontractor or supplier level).

Another significant step in the cost estimate is to calculate the required direct labor hours for fabrication and assembly of parts into a completed aircraft. A phenomenon first noted in World War II aircraft production was the reduced hours it took to produce each subsequent lot of aircraft. This phenomenon was termed a learning curve because when cumulative aircraft quantities along with hours per aircraft were plotted on a log-log chart, a very predictable and nearly straight line resulted. With advances in statistical computation packages, these plots can be done arithmetically, resulting in a curved shape on a linear-linear graph. Learning curves varied by phase of manufacture (production, assembly, final assembly, and so forth), type of aircraft, and company but were fairly consistent within
each aircraft program. Metal fabrication may have an 85 percent learning curve, while assembly may have a steeper curve of 80 percent, due in part to fewer automated processes used in assembly than in fabrication, so labor hours constitute a higher percentage of total costs in assembly and, hence, lend themselves to “learning.”

A wealth of data exists for labor hours expended by lot for historical aircraft production, and these data can be regressed against some physical aspect of the aircraft (weight, for example) to get an hours-per-pound calculation for direct labor hours. These kinds of regressions result in CER models or formulas. An analyst preparing an estimate can access any number of these CERs, enter the physical characteristics of the aircraft, and get the calculated labor hours for the entire production, based on an assumed learning curve. These hours are multiplied by estimated fully burdened labor rates for a particular company by category by year, which converts the hours to dollars. Direct manufacturing labor hours are often multiplied by factors to estimate support functions, such as quality control, recurring tooling hours, and so forth.

Historical learning curves should more correctly be termed cost improvement curves because the successive reduction in labor hours by lot stems from more than workers’ learning how to do their tasks more quickly. Industrial engineers develop what are called standard hours for each task or operation that must be performed to produce a finished aircraft. In theory, mechanics could complete their tasks in the number of standard hours if they had all the tools and parts available for their tasks, understood their tasks, had performed them many times before, encountered no difficulties, took no breaks during the day, and were performing value-added work for eight hours per day. As a matter of practical fact, these conditions do not exist in the real world.

Realization factors are developed to predict performance against the standards and are calculated by dividing actual hours required to complete a task by the standard hours. Early in a program, the realization factor may be as high as seven or eight to one, meaning that it is taking seven or eight hours to complete a one hour task. As production continues, realization may approach two to one as a theoretical minimum. Thus, the learning part of the cost improvement curve is described by the realization curve.
But historical cost improvement curves also include reductions in standards, as better tools, equipment, or processes are introduced. One example is when laser projection replaces hard templates in hand layup composite part fabrication. With laser projection, an outline of the required ply location is projected onto the tool, and workers lay down the ply directly without dealing with the hard templates. The work of retrieving the template, placing it on the tool, marking the intended location of the ply, removing the template and returning it to storage disappears. When a new process, such as laser projection, is introduced, a stair step downward on the cost improvement curve would be expected because the new process requires fewer standard hours to complete. This may be partially offset by a slight loss of realization as the workers learn the new process. In essence, the historical “learning curves” involve literally hundreds of these phenomena over time, as an overall learning curve for the life of the aircraft production line reflects many changes to standards and realization.

With that simplified explanation of the development of a cost estimate, the basic question becomes one of deciding whether lean manufacturing should produce savings greater than the historical material improvement curves, whether lean reduces standard hours, realization, or both, and whether reductions observed in historical data were the results of activities similar to lean manufacturing but not termed as such. For example, if under lean standards a more automated process is introduced at the beginning of a program, it would be safe to assume that the hours required to perform the task on the initial aircraft should be lower than previous aircraft produced in the old manual way. This new process should have lower standard hours (at least direct labor hours) than the previous aircraft (called a lower T1). But the question facing the cost analyst is whether this process would experience the same learning (realization) over time as past programs, because of its lower labor content to begin with, with less human activity (hours) to improve upon. In most automated processes, little reduction occurs in on-machine time after the first few parts are made.

In addition, if lean manufacturing is implemented in the production planning stages, lower T1s should result as manufacturability problems are eliminated in the design phase, so scrap, rework, and repair should be significantly reduced. With those problems eliminated,
can historical cost improvement curves be expected, or should less subsequent improvement (flatter realization) be expected as the normal learning is “shifted forward” on the curve, so that the kind of efficiencies normally experienced on aircraft number 20 may now be achieved on aircraft number 2?

In the purchased material area, are the reductions in supplier prices due to such lean initiatives as strategic sourcing different from the savings traditionally experienced in material improvement curves? Can lean savings be subtracted from these material improvement curve calculations?

Lean manufacturing proponents suggest that because of *kaizen* and continuous improvement philosophies in the lean system, learning curves do not necessarily have to flatten, even in an environment of increasing automation. A sustained focus on sources of waste in the system will lead to continued improvements. However, this contention is by no means universally accepted and in fact was called “the debate of the century” at one manufacturing plant. Using lean manufacturing techniques, they expected a lower first unit cost than predicted using historical CERs but projected ongoing learning curves of from 3 to 7 percent flatter than history would suggest. Other companies offered the counterargument that historical learning can still occur using continuous improvement and other lean tools, a perspective that has also been found in the literature. However, lean implementation in defense aircraft manufacturing is still too sparse and too new to have resulted in conclusive data supporting this argument. Furthermore, much of what companies presented as labor savings from lean manufacturing were really products of increased automation, hence, reductions in standard hours. In these cases, flatter learning curves (realization) should be expected.

But cost analysts in DoD and industry are being badgered to accommodate for claims made by proponents of lean and to reduce their estimates from what traditional CERs and other estimating methodologies would produce. Clearly, if lean practices are successfully implemented throughout all aircraft manufacturing processes, the traditional estimates and methodologies should overestimate costs, all else being equal.
DoD must decide how it will accommodate manufacturers’ efforts at improving their processes. There are two main alternatives. The more aggressive approach suggests a wholesale percentage reduction in forecast cost due to lean manufacturing. This entails accepting the prime contractors’ claims that they understand lean principles and will be able to transition their pilot project successes to the new aircraft production lines. However, as has been previously described in this report, a number of technological innovations that broadly enhance lean manufacturing and lead to efficiency improvements are already in use on the factory floor and have to some extent been incorporated in the actual hours-per-pound data used in developing cost estimates of aircraft. A global percentage credit would probably involve considerable double counting of recent technological improvements.

The alternative is giving credit to measurable, proven initiatives only. This is a more conservative plan but has some benefits. First, it enforces a standard of measurability on the manufacturers. Specific attention can be given to the avoidance of double counting improvements by requiring that lean improvements be traceable to specific Work Breakdown Structure (WBS) elements and into work and material standards in terms of hours or dollars. However, it may be more complicated, as government personnel will have to examine each initiative individually. Also, it may have the unintended side effect of getting manufacturers to reduce their focus on a major change effort throughout the organization. Rather than a global and integrated transition to lean, this conservative approach focuses on limited improvements. The concern is that companies will respond by focusing their efforts on “low-hanging fruit” rather than on a wholesale alteration of their processes. Larger-scale change efforts may be needed to capture the synergistic efficiencies where proponents of lean manufacturing say the real savings are to be found.

Based on the limited evidence of complete plans among aircraft manufacturers to plot their broad transition to lean, this second conservative approach to estimating lean savings is the one recommended at this time.

In our view, some safe, general assumptions can be made and incorporated into estimating methodologies, although they must be done with extreme care.
• Two separate initiatives designed to reduce labor hours in the production of a particular part should not be calculated against the same baseline. They should be calculated sequentially, so that one reduction should be taken against the baseline and the second reduction be taken against that result (a lower number).

• To the extent that new processes are incorporated into manufacturing, or any other production or support areas, a reduction in the standard hours to perform each task can be applied to the output of historically based CERs as a T₁ (or Tₙ if applied later) adjustment. These are called displacements from the learning curve. Assuming that loss of learning from the new processes is negligible, this results in a new cost curve parallel to the old one, but with lower values. The question then is whether the new curve should be parallel to the old one, be flatter, or even be steeper. We found insufficient evidence to support any of the three alternatives based on the limited lean implementation data available. An industrial engineer can be very helpful to the cost analyst in determining the adjustments in standard hours, realization, or other factors that could affect the shape of the curve in individual aircraft estimating situations.

• Because the focus of lean is process-oriented in nature, we would expect, however, that traditional learning (realization) will occur at no faster rate than history would suggest (curves should be the same or flatter). Lean may compress more learning in the first units, which may appear to produce steeper curves initially, but these will flatten later.

• Continuous focus on lean will be required to match the slope of historical curves because of the reduction in standard work content earlier (lower T₃s) and compressed learning at the front end with proper lean planning.

• Much of this continuous improvement focus must be highly incentivized, either using “carrots” (perhaps by allowing companies to keep a higher percentage of each dollar they can save) or with “sticks” (hard-nosed negotiating, more dual sourcing with competition incentives). With the government normally negotiating follow-on lot prices using previous lot actual costs (especially in a sole-source environment) and adding profit to
that base, contractors must have some incentive to continue the journey to lean and continuously reduce their cost baseline.

- Reductions in material prices may be greater than historical material improvement curves would indicate if primes work with their subcontractors and suppliers in implementing lean. The impact of this approach would have more impact on higher value-added suppliers. Raw material and commercial like purchases should exhibit more of the historical market price phenomena (if there are any reductions at all), especially in areas where DoD buys a small percentage of the overall market. One exception may occur in many large buys of raw materials (group purchasing agreements) where strategic sourcing agreements are used and specific savings may be achievable.

- The overhead area is probably the place with the least likelihood of significant savings. Unless a greenfield facility can be built, aircraft plants must still be illuminated, heated, and protected, whether all the space in a plant is being used or not. Putting more manufacturing into fewer plants and closing others is the only way to reduce costs in the physical plant area. Application of Acquisition Reform (AR) resulting in decreased oversight, fewer unique government requirements, and the use of contractor cost data systems rather than government ones can also help reduce overhead expenses not related to factory operations.

- Support labor, which is often factored from manufacturing labor (QC, for example), may have to be decoupled and estimated on its own. For example, laser ply alignment can reduce fabrication hours for composite parts by 10–15 percent, but the task of inspecting the part does not change, unless inspection technology is improved. Thus, the factor for QC may have to be increased or estimated separately. The same applies to recurring tooling labor. Again, the cost analyst will need the help of a good industrial engineer until historical data that incorporates lean become available.

Many of these techniques have been studied and documented by the aircraft companies. The F-22 Production Cost Reduction Plans (PCRPs) are a compendium of efforts by the tri-companies to reduce the cost of aircraft production. Some of these include lean initiatives. The basic methodology used by both the government and industry
estimators was to develop a baseline estimate then apply each PCRP discretely to that baseline to produce their overall estimate of program costs. Until actual costs for the F-22 or other aircraft produced in a lean environment are available, this may be the only viable approach open to cost estimators.