INTRODUCTION

In this chapter, we describe in somewhat more depth the complexities of how lean production affects the manufacturing function. We look at both major process changes and enabling tools. We provide specific examples of lean implementation efforts and the savings that resulted. The companies that participated in this study demonstrated many lean pilot projects where savings were achieved in manufacturing functions. In terms of aircraft recurring labor costs at the prime contractor level, manufacturing constitutes more than half of the direct labor hours, so it is a very important area for focusing lean manufacturing techniques. The CCDR definition for manufacturing is in Appendix C.

At the most basic level, lean manufacturing is about making better products more quickly and at lower cost with minimum waste, which places a great deal of focus on production operations in the factory. A lean factory is one where machines are arranged in an orderly fashion to enable rapid and efficient product movement. It is a factory with minimal work-in-process and finished goods inventories, where products are built only when customer orders are received. It is a factory where workers pay attention to the quality of the product they are building and can perform inspections and simple machine maintenance. A lean factory is clean and orderly, without dirt or untidiness that can harm the product and without potential dangers that can harm workers.

Lean manufacturing operates on two levels on the factory floor. First, lean incorporates such large-scale philosophies as producing
goods according to customer demand (pull production), arranging tools so parts flow smoothly and efficiently through the production stream (cellular manufacturing, producibility), and changing tools quickly to produce different parts (flexibility). Second, lean manufacturing is about incorporating a wide variety of specific best practices. These range from the kitting of parts and tools to such simple improvements as shadowboxes to store tools to the 6S philosophy about keeping the factory clean and safe to digital technologies aiding manufacturing, such as electronic work instructions.

LEAN MANUFACTURING IN THE FACTORY

Lean manufacturing focuses on cutting costs and waste, but it goes well beyond Taylor’s "scientific management" attention to how the specific tasks are performed. Instead, lean manufacturing pays attention to two different aspects of the production process, the value-added steps, which include all work that contributes directly and positively to the manufacture of the product, and the non-value-added work, which includes everything else done to the product and in the plant. Machining time, when the product is actively being formed, shaped, or otherwise manipulated to bring it into conformance with the final design, is value-added work. Many sources of non-value-added work exist, including rework of a part or subassembly resulting from out-of-control processes. All non-value-added work can be classified as waste.

Much previous work on efficiency improvements and cost reduction in the factory has focused on the value-added portion of the work. For example, making production processes more efficient through investments in new machine tools has been an ongoing effort. Reducing the non-value-added portion of processes received less attention before the lean manufacturing. A notional example, as seen in Figure 6.1, reveals why the focus on the total value stream offers powerful insights.

In the base case, 20 percent of any particular effort might be related to value-added effort and 80 percent non-value-added. One common example is cycle time. In this case, 20 percent of the time the part is in the factory it is actually being worked on, and 80 percent of the time it is either in beginning inventory, awaiting a process,
awaiting transport to another tool, being moved to another tool, or in final inventory, awaiting installation or delivery to the customer. Base case 1A graphically demonstrates how periods of activity are interspersed with significant amounts of time that the part is spent in queue or traveling. The second depiction of the same base case (1B) totals the value-added and non-value-added portions of the time to arrive at 20 percent and 80 percent. (Note that 80 percent is actually a very low proportion for non-value-added cycle time in most non-lean factories—more than 95 percent was often mentioned as the non-value-added cycle time in a factory.) In the first cost reduction example, efforts focused on the value-added portion of the process have yielded a formidable 50 percent reduction in value-added production time that results in a cycle time of 90 percent of the base case. Lean manufacturing advocates attention to the non-value-added portion as well, as in the second cost-reduction example. Here, a 50 percent reduction in both contributors to overall cycle time results in a cycle time that is one-half its original figure, with 80 percent of the savings achieved through the reduction in non-value-added activities. Of course, in terms of costs, the value-added time (for example, on-machine time) may be much more expensive than
the non-value-added time, so analyses must evaluate all aspects of the flow time/cost processes to develop optimal lean manufacturing production flows.

**PULL PRODUCTION**

Ideally, the manufacturing process does not begin until an order from a customer has been received, which should send a signal to start production. Rather than building to some set production schedule, in lean manufacturing, orders from the customer start the production process. This helps reduce finished-goods inventories, as each item produced has a customer already. Producing to customer demand also reduces waste as unwanted output does not sit in finished-goods inventory, perhaps getting damaged or becoming obsolete. But producing to customer demand requires that lean companies develop flexible production processes to respond to the specific demands of each customer, to quickly produce the desired configuration. The length of time to produce a finished good, or cycle time, needs to be minimized so that specific customer demand can be met quickly and efficiently. This involves a drastic change of mindset for many companies that build according to a schedule that optimizes machine use, producing inventory that then must be aggressively marketed to customers, sometimes at discounted prices to move the products.

This lean ideal denotes a significant departure from historical manufacturing planning. Rather than producing directly to orders, managers traditionally would predict demand for their product and plan their production to match this prediction. If they guessed wrong, either expensive finished goods inventory would stack up waiting to be sold or profit opportunities would be missed as customers wanted more output of a different type than the factory could produce. Producing to customer demand eliminates these problems but requires a different production philosophy combined with very efficient processes to meet customer needs in a timely manner.

Pull production is to a large extent built into the aircraft production mindset. Both commercial and military aircraft production are geared toward specific orders from customers. Prime military contractors build planes that have been actually committed to by the customer, to an agreed-on schedule instead of speculatively. Aircraft
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Manufacturers are in an excellent position, therefore, to work backward from known delivery dates to schedule production. Cycle time reduction can still be an important area of cost saving and improved customer service. Properly applied techniques from lean manufacturing can reduce this cycle time and help keep costs down. Taking a longer time to build an aircraft means that both costs and the risk of quality problems increase as the aircraft accumulates costs based on its status as part of Work in Progress (WIP) inventory, without operational availability to the customer/operator.

CELLULAR PRODUCTION AND SINGLE-PIECE MANUFACTURING FLOW

A lean factory looks very different from a factory engaged in batch production in a number of ways. An experienced eye might first notice the different arrangements of the machine tools, which reflects a number of related lean principles and best practices such as pull production and inventory reduction.

Traditionally, manufacturing plants were organized into what can be called departments based on the type of processing that was being done. For example, basic metal machining done on similar tools would be in one department. All the related machine tools, such as grinders or cutters or drilling machines, would be located in the grinding or cutting or drilling department. Parts and assemblies would move from area to area depending on what needed to be done to them next. Any particular part could move back and forth into and out of one department several times. A considerable amount of movement was involved, as well as waiting time for parts to be picked up and moved around. Since it is costly to move parts individually, usually some batch of a number of parts would be worked on and finished and the entire batch would be moved at one time.

In the ideal lean manufacturing plant, tools are arranged in cells by product. The focus within the cell is not on the function or on the particular process but on the part or product. All the machines that work on a particular part are in sequence so that as soon as one process is finished, the part can be moved to the next operation. Keeping the product moving reduces the amount of inventory stacked up waiting to be worked on. Also, a quality problem caused by one pro-
cess becomes quickly obvious in the next process. (Under traditional batch manufacturing, a process that causes a quality problem perhaps because of an out-of-tolerance machine may not be discovered until the entire batch is finished and moved to the next department.)

A simple example demonstrates the benefit from the reduction of batch sizes (see Table 6.1). In this example, each part must go through four processes before it is completed. Processing one part by any process takes one unit of time. The columns labeled $T_1$ through $T_{10}$ represent the 10 units of time in the process, with contents of that cell representing what has been worked on in that time period. (The moment in time represented is actually the end of the time period, $T_n$.) $S_1$ through $S_4$ refer to the different machine stations or processes that create the finished product.

In the first case, the batch size is three. Each batch is represented here with a different letter, so that its progress can be tracked through the “factory.” As parts are worked on at a particular station, they move from the left side of the cell to the right side of the cell, signifying a move from inventory waiting to be worked on to inventory that has been processed and is waiting for the completion of the whole batch so it can be moved to the next station. Finished items are expressed in upper-case letters to symbolize the higher value of these items that have been processed. The group of parts does not move to the next station until all three parts in the batch are complete.

In the first example, there is one unit of finished inventory at the end of ten units of time. A customer must wait ten units of time to receive a single unit of the product that it has ordered. Eleven parts make up the WIP inventory. A processing or quality problem caused at the first station ($S_1$) would not be discovered until the first batch of parts moves to the second station during the fourth time period ($T_4$), possibly resulting in four scrapped parts before the out-of-tolerance situation was discovered and corrected. If quality inspection occurs at the very end of the production process, as many as 13 parts would be scrapped or reworked, depending on what process was causing the problem. (If it was the first process, the three parts that had moved to final inspection; the nine parts that were undergoing pro-
### Table 6.1
#### Case 1: Batch Production

<table>
<thead>
<tr>
<th>Station</th>
<th>T_1</th>
<th>T_2</th>
<th>T_3</th>
<th>T_4</th>
<th>T_5</th>
<th>T_6</th>
<th>T_7</th>
<th>T_8</th>
<th>T_9</th>
<th>T_10</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>aa A</td>
<td>a AA</td>
<td>AAA</td>
<td>bb B</td>
<td>b BB</td>
<td>BBB</td>
<td>cc C</td>
<td>c CC</td>
<td>CCC</td>
<td>dd D</td>
</tr>
<tr>
<td>S2</td>
<td>aa A</td>
<td>a AA</td>
<td>AAA</td>
<td>bb B</td>
<td>b BB</td>
<td>BBB</td>
<td>cc C</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S3</td>
<td>aa A</td>
<td>a AA</td>
<td>AAA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>aa A</td>
</tr>
</tbody>
</table>

NOTE: Each numbered T designation represents the end of a given time period. Lower-case units on the left side of each cell are waiting to be worked on. Upper-case on the right side of the cell indicates parts that have been processed and are waiting to be moved to the next function. Upper-case units finishing the final process (S4) have completed all four stations and are finished products.
cesses two, three, and four; and the unit being worked on in station one while the problem was discovered would all have to be fixed.)

In the second case (see Table 6.2) the batch size is one. As each part is finished, it is moved immediately to the next machine where processing begins. (Note that the inventory waiting to be worked on, represented as lower-case letters at the left side of the cells in Table 6.1, does not exist in this second example.)

In the second table, there are seven finished parts at the end of 10 units of time. A customer only has to wait four units of time until the first part is ready for delivery. There are only three parts in WIP inventory at the end of time 10, and no more than four parts in inventory at any given time. Parts are never in queue awaiting work but are undergoing nearly constant processing.

It should be noted that, over a longer period of time, the number of finished parts in the first process approaches those in the second example. At the end of 100 units of time, single piece flow production would result in 97 parts. The three-piece batch process would result in 91 parts. However, the one-piece flow example does have the advantage that quality and machine problems are discovered more quickly. A processing problem at the first station (S1), whether caused by a machine that is out of tolerance or by error from an insufficiently trained operator, would be discovered quickly, during the second time period (T₂), after the part moved to the second station (S₂). Remedial action could quickly fix the offending problem before many parts that had to be scrapped or reworked were made. Even if all quality assurance activities took place at the end of the production process, after the parts are in station four (S₄), there still would only be four parts that need to be scrapped or reworked. This is a sharp contrast to the batch manufacturing example, where first station problems would be discovered at the second station, after three bad parts have been built, or perhaps in quality assurance after production is complete, when at least 12 parts would need to be scrapped or reworked.

Single-piece flow production is intrinsically related to cellular production, with machines in successive operations close to each other with related cells abutting one another. Parts move quickly between
### Table 6.2: Single-Piece Flow Production

<table>
<thead>
<tr>
<th>Station</th>
<th>T_0</th>
<th>T_1</th>
<th>T_2</th>
<th>T_3</th>
<th>T_4</th>
<th>T_5</th>
<th>T_6</th>
<th>T_7</th>
<th>T_8</th>
<th>T_9</th>
</tr>
</thead>
<tbody>
<tr>
<td>WIP</td>
<td>1 part</td>
<td>2 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
<td>3 parts</td>
</tr>
<tr>
<td>Finished</td>
<td>A</td>
<td>AAA</td>
<td>AAB</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>S1</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>D</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>S2</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>S3</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>C</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td>S4</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>A</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
<td>B</td>
</tr>
</tbody>
</table>

**NOTE:** Each numbered T designation represents the end of a given time period. Units finishing the fourth process (S4) are complete.
stations, eliminating the non-value-added work of transportation and reducing cycle time. Parts are processed individually and then easily moved a foot or two to the next operation.

Alternatively, under the “traditional” model, where the processes occur in distinct departments, it makes more sense to produce parts in a larger batch rather than singly, to spread the costs of transportation to the next process across more than one part. However, moving the parts also adds to cycle time to produce the part and increases WIP inventory, which may be further increased if no one is available immediately to move the product. During this delay, the product might be harmed by environmental contaminants, physical damage, or even obsolescence. The delay might also increase the costs of quality, as has already been discussed, when problems created by one machine are not discovered until the entire batch gets to the next station instead of after a single part moves on. Batch production deals with quality problems by maintaining an inventory of parts that have undergone the first process and would allow the second machine to keep working even if defective parts are found or if parts are damaged in transit. Inventory provides a buffer in batch manufacturing, although a buffer with significant costs. The batch method also increases required floor space to store the excess inventory and any extra machines required to maintain production levels, given inefficient processing.

Note that batch manufacturing should not necessarily be considered an example of poor management. If lean manufacturing principles have not been incorporated in the rest of the plant, batch production offers distinct benefits. For example, if the parts produced at the plant are widely varied, there might be significant setup times to reconfigure the machines for different types of parts. Producing similar parts in large groups is seen as being one way to increase machine utilization rates. Without pull production, parts may be produced for inventory rather than for particular customers. Also, if one machine broke and required repair, the next machines in the process would not necessarily lie idle if they were working with batch inventory. However, the goal of lean manufacturing is to make parts efficiently in batch sizes of one to avoid having to maintain these buffers. If lean manufacturing techniques are prevalent throughout, the costs inherent in batch production can be avoided.
Lean/best practice manufacturing does not assume that lengthy setup times or temperamental machines prone to breakdowns are normal aspects of production. Rather, it looks at these as issues that can be solved through careful analysis. Manufacturing engineers and skilled, trained operators can engage in short-term or long-term projects to deal with these issues. Lean manufacturing also consciously considers ways of reducing non-value-added stages as well as making value-added steps more efficient. This has driven the attention to reducing cycle time and transportation to eliminate costs.

Cellular production involves intense analytic study of the factory floor to enhance flow of the product through the factory. Machines should be located so that each product can move smoothly, and for the shortest distance, during processing. (Machines are often arranged so that the manufacturing cell has a U shape, to minimize part and people travel.) Improving flow also helps cut cycle time of manufacturing, and work in process inventory, with its attendant costs. Also, the number of operators may be reduced; fewer people are needed to move large batches of product from one machine to another.

Moving to a cellular lean production framework often involves the creation of pictures mapping out part or person travel. These are occasionally referred to as spaghetti charts, as traditional movements often resemble a big bowl of pasta, with the strands representing the travel path of the part or person. In contrast, a plant laid out to minimize part movement has a much simpler chart (see Figure 6.2.)

Note that the benefits of cellular production are limited unless the entire manufacturing floor is reorganized into cells. Unless all cells in the plant are lean, or the lean cells are on the critical path through the factory, parts may speed through some areas and sit around in other areas waiting to be worked on. Some WIP inventory will be reduced resulting in cost savings, but these savings may be small without a consistent plantwide effort to cut inventory.

In fact, lean manufacturing specifically examines this possibility as it calls for a continual analysis of bottlenecks, areas where inventory is building up because of poorly organized processes or insufficient
The Effects of Lean Manufacturing

Preparation time—3 hours. Walk pattern—26+ trips. Process time—8.4 hours.
SOURCE: Northrop Grumman.

Before lean event

Preparation time—0 hours. Walk pattern—0 trips. Process time—1.62 hours.
SOURCE: Northrop Grumman.

After lean event

Figure 6.2—Before (Nonlean) and After (Lean) Process Flows
Manufacturing machine capacity. Focused remedial actions called kaizen events can be used to study and (ideally) quickly correct problem areas. Because lean manufacturing looks for a continual improvement\(^1\) of flow through the plant, and as each bottleneck is removed and production is speeded up, by definition a new spot can be improved.

In production organized in assembly lines, such as in car manufacturing, this means that the pace of production is continually increased. Bottlenecks are identified at areas where workers can no longer keep up the pace. If they cannot perform the required functions, they can stop the assembly line until the bottleneck is resolved. By speeding up the line, assembly line production offers an efficient way of identifying areas that increase overall cycle time. This technique is less applicable in aircraft manufacturing, where low production volumes combined with an extremely complex product mean that assembly lines are not used.

**TAKT TIME**

*Takt* time describes how frequently final outputs should be produced in order to satisfy demand. It is the ratio of how much time is available in a given period divided by how many parts or products are demanded by customers in that time. So if customers want two parts every day, and there is one eight-hour shift, the *takt* time is four hours. Under the lean manufacturing system, this number drives operations in the factory. The system is set up so that one final product is produced every four hours. All areas are organized so that the associated tasks can be performed in that amount of time, before the part moves to the next station. The work is “balanced” so that all workers are fully employed during the *takt* time period. If demand increases, *takt* time decreases, and the system is reorganized (perhaps workers are added) so that parts can be produced more quickly. The concept of *takt* time and line balancing are perhaps more obvious drivers of operations in high-volume factories where many items

\(^1\)Lean manufacturing calls for attempts for continuous improvement in all areas, from initial design to final delivery. Every process and function should be the target of ongoing analysis and study to improve it, to make it more efficient, to reduce its costs. Hence, true implementation of lean manufacturing is not a one-time event but rather an ongoing process involving considerable commitment.
are produced in an hour on an assembly line than in aircraft factories where high volumes might mean 10 aircraft in a month with a takt time of two work days. Balancing activities so that all workers are fully employed for the two-day takt time is a very complex task, although it can be done. Takt time can also be used to plan production of subassemblies so that they are produced at the proper rate and can be assembled to produce aircraft at a steady pace.

*Takt* time can help planners identify tooling and manpower requirements. As orders for aircraft are generally known in advance, *takt* time can be used by manufacturing engineers for advance planning factory operations so that production operates efficiently. Ideally, the ratio helps planners balance different aspects of the production process so that they are produced in approximately the same time, enabling single-piece flow and reducing inventories.

**VISUAL CONTROL**

Visual control consists of many initiatives related to maintaining product flow. Production workers and others in the plant should be able to easily determine what is in queue to be worked on next. Operators working in the plant as well as managers walking through it should see a clean area without a lot of inventory, where SPC charts let everyone know where improvement efforts must be focused, where workers can tell at a glance if they have the proper tools and parts to do a job. Similarly, machine controls should be obvious so that mechanics and others can easily tell if they are running properly.

**Housekeeping**

One more prosaic contribution to the overall quality effort occurs as a function of keeping the factory clean. This contributes to better visual controls. With no unnecessary material in the way, production problems become more obvious, parts and tools can be located more quickly, and products are not at risk from foreign contaminants. In aircraft production, housekeeping is particularly important because of the risk of damage from FOD.2 Keeping the plant clean also makes

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2Foreign object debris or foreign object damage.
machine problems more obvious. If the floor under a machine is generally kept clean, oil leaks become immediately apparent.

Lean housekeeping is often referred to as the “Five Ss,” which allude to five Japanese words regarding keeping cleanliness in the plant. Different translations have produced various “S” words like sort, sweep, simplify, straighten, shine, sustain, standardize, and self-discipline. Most U.S. facilities have implemented a “Six S” program, where the sixth S stands for safety.

**Location of Tools/Shadowboxes**

Another area where visual control applies is tool storage. Mechanics use a considerable variety of hand tools (as opposed to large fixed tools) in assembly operations. Traditionally, these may have been kept in personal toolboxes located where particular mechanics spent their time. If they wanted a particular tool, they searched through their toolbox to find the tool then brought it back to the stand. Company-owned tools might also be kept in a centralized tool crib (which may or may not be nearby) where mechanics had to go to and ask for the tool they needed. In a lean plant, however, tool cribs are near where tools are needed. This cuts wasted time and motion on the part of mechanics. Another technique is for tools used in a particular area to be stored together in “shadowboxes,” which take several forms. Some companies draw outlines of particular tools on boards then put hooks to hang the tools on. The outlines function as a “shadow” of the tools, and it is instantly clear if any tool is missing or is stored in the wrong place. Mechanics know where the tools are without searching for them and know where to return the tools. A similar concept is to use foam inserts with cut-outs for each tool. In both concepts, groups of tools used on a single process can be stored together. When mechanics start working on a new part, they can pick up the entire tool set at once. Also, mechanics can move smaller shadowboxes to where they are working to reduce the trips they take for tools. Some companies purchase tools for particular tasks much as they package the parts together (see kitting, below) for the same assembly task. Thus, the worker has everything required to complete a specific task at the beginning of work.
Cost reductions from a rationalized system for tools\(^3\) result from decreases in direct labor hours, cost of tool inventories, and reduced defects. With tools properly stored, tool inventories are easier to manage and extra tools can be eliminated or never purchased to begin with. Each mechanic becomes more efficient because the right tools are always available, perhaps allowing for reduced head count. Furthermore, there may be increased quality stemming from the proper tool being used for each task. Determining the exact amount that shadowbox concepts could save would require before and after studies of the amount of time mechanics spent searching for tools, determining excess tool inventories, and the cost of quality problems attributable to incorrect tools being used.

**Shadowbox Kitting**

A similar innovation is the preparation of packages of all the parts that the mechanic needs to complete an assembly task, called *kitting*. With properly prepared kits containing all the required parts laid out in shadowbox format, mechanics know immediately if all the parts are available before starting the assembly of a particular item. They can pick up (or have delivered) the entire set of parts needed at one time and bring them to the assembly location, reducing travel time spent locating parts. It reduces the likelihood of the wrong part or fastener being used. It would also reduce WIP inventory, as mechanics would not start on jobs that they could not complete until all the parts were available. Note that kitting also can help enable the pull manufacturing system, as empty kit boxes can be used as a physical replacement for *kanban* cards and sent to the beginning of the line to signal when production of a particular part should start. Figures 6.3a and 6.3b demonstrate typical part presentations before and after shadowbox kitting.

Cost reductions from shadowbox kitting result from the reduced time needed to locate parts by mechanics, which could lead to reduced head count. (Some increase in support labor must be acknowledged for those who prepare the kits for the mechanics on

\(^3\)See preceding chapter on tooling.
Figure 6.3a—Before (Nonlean) and After (Lean) Shadowbox Kitting of Parts the assembly line. Even if a one-for-one trade in direct labor hours for support labor took place, however, two reductions in cost occur. The first stems generally from lower support labor hour costs, and
the second is the reduced cycle time in the assembly process. (The kitting can be outsourced to take advantage of suppliers’ generally lower labor rates.) Kitting can also result in reduced cycle time and

**Figure 6.3b—Before (Nonlean) and After (Lean) Kitting of Tools**
lower WIP inventory. Part kitting helps rationalize the inventory system, perhaps making it obvious which parts are not currently being used in production so that they can be sold off and the space required for inventory can be reduced. Generalized savings estimates would vary by plant layout, complexity of the assembly, and even worker experience. However, savings could be determined by undertaking a before-and-after study of the time workers spent searching for parts (which could then be applied to additional assembly work, thereby reducing cycle time) and the savings related to reduced inventory.

MANUFACTURING BEST PRACTICES THAT ENABLE LEAN PRODUCTION

A considerable number of practices can help reduce costs and improve quality. As such, they can be incorporated into the lean manufacturing system as they reflect the lean philosophy of pushing for continuous improvement.

Total Productive Maintenance (TPM) offers workers job enrichment through greater responsibility in taking care of their machines. By doing regular maintenance tasks according to a predetermined schedule, the number of catastrophic machine breakdowns should be reduced. The advantage is that operators no longer must wait for dedicated maintenance personnel to perform these tasks, or they can perform the maintenance tasks during normally unproductive operator time. It may also give the workers a greater sense of ownership and pride in the machines and the processes. Ideally, the machines should have simple visual controls indicating how well they are working so that mechanics can be alert to problems earlier.

Electronic work instructions offer workers an information-rich reference to use during fabrication and assembly. Computer terminals placed near workstations can be accessed to provide lists of parts and tools that are needed, links to drawings and bills of materials, and specific step-by-step instructions on what to do. In some cases, step-by-step computer-generated pictures show the entire assembly sequence to the mechanic. Electronic work instructions are a particularly valuable tool during the complex production processes that characterize aircraft manufacturing. By contrast, in high-volume
assembly line manufacturing, the work is broken down into small component steps that are performed repetitively by the same person. *Takt* time might drive balanced processes that take as little as a minute or two so one worker becomes quite expert at a specific task. Aircraft assembly volumes do not allow for such specialized division of labor, and processes tend to be more complex. Electronic work instructions are one tool to provide information to workers doing particular processes relatively rarely—perhaps once or twice a week in a high-volume aircraft line. Electronic work instructions can help workers figure out quickly how to proceed and help eliminate quality problems and associated waste from preventable mistakes. In addition, updated instructions reflecting incorporation of the latest engineering change orders/configurations can be provided immediately to the assembly line, thus preventing scrap or rework. In one company, electronic work instructions were expected to reduce total direct manufacturing labor by about 5 percent.

*Markings on floor to position tools and equipment,* or even places to bolt tools directly to the floor, reduce setup time in assembly and can improve fit as well as reduce waste from product defects.

In automobile plants, *Andon,* or ability of operators to stop the assembly line in case of problems, has been much touted. Aerospace has relatively low volumes and more complex operations performed over longer periods, so pulling a cord to stop the line is less applicable. However, mechanics should have the ability to stop production and alert management to problems. Recognizing the need for workers to provide feedback to engineers quickly, some companies have relocated engineers close to assembly areas and provided workers with “virtual hotlines” to contact the engineering/manufacturing staff rapidly when problems arise.

**SUMMARY RESULTS ON IMPLEMENTATION OF LEAN MANUFACTURING**

Visits to airframe manufacturers revealed a range of interesting projects, implementation strategies, and change philosophies. The prime contractors that participated in this study offered the results of a number of lean manufacturing projects. In many cases, these showed considerable savings in labor hours, in cycle times, and in
floor space. All of the primes had at least initial experience with pilot projects on the factory floor, and some of this experience was quite extensive. These pilots are presented as they stood in the summer and fall of 1998. Since then, additional evidence may have been collected on these projects and additional projects.

It is useful to keep in mind the limitations of using pilot project savings for larger-scale implementation plans. One issue is how the projects were selected and whether they are representative of the entire manufacturing operation. They may have been ones where initial improvements were expected to come more easily (perhaps areas with chronic problems), the so-called “low-hanging fruit.” Another is that smaller-scale changes may be easier to implement because less organizational or worker support is required. Scaling up lean techniques throughout the enterprise may require a considerable organizational effort. In addition, the “Hawthorne Effect” (Roethlisberger and Dickson, 1939; Mayo, 1945) may be operating during pilot programs as workers feel that management is paying attention to their analyses during *kaizen* events and hence increase their efforts. With these caveats in mind, what follows is a sample of larger lean visions, lean philosophies toward particular manufacturing areas, and results from some pilot projects.

**Specific Examples of Savings from Lean Implementation**

One company typical of those RAND visited was focusing its lean vision on a number of elements:

- Establishing a visual factory and pull system.
- Shortening cycle times and manufacturing spans.
- Focusing fabrication and assembly on value-added tasks.
- Standardizing support processes where practical.
- Reducing support labor costs.
- Reducing overall inventory investment.
- Providing timely, accurate data for decisionmaking.

Lean implementation has enabled some cycle time reductions at plants. For example, the span time of one product was reduced by 40
percent over four years. Credit was given to lean manufacturing initiatives as well as other efforts.

An example at another plant pointed out some of the contradictions in lean implementation. In one small extrusion processing cell, the number of employees was reduced from six to two after lean principles were instituted. The tremendous labor savings—66 percent—is not unique among efforts this small, but we found little evidence that such savings had been achieved in larger scale implementation efforts. It also points out one issue when implementing lean in the defense aerospace sector—the other four employees were surplused, by seniority. The firm indicated that the decision is “lean with fewer jobs or not lean with no jobs.” Labor unions must share this philosophy if factories are to be made more efficient. While worker reductions may be required in the military aircraft sector, proponents of lean in the commercial world stress that cost reductions and quality improvements when implementing lean should result in greater volume of sales so workers may not have to be let go.

One company expected overall savings from lean manufacturing to be in the range of 10 to 15 percent savings. They stated that two-thirds of the effort in being lean or becoming lean occurs during development, with one-third occurring later on in production. However, 80 percent of the cost savings occur during production. The company claimed that using the new technologies without lean implementation would result in only 2 to 3 percent savings. Investments in lean programs were considered worthwhile because if the changes were implemented properly they would produce rapid paybacks.

**Lean Transformation at Brownfield Plants**

Any new production philosophy is easier to implement at new facilities than at old, so-called “brownfield” plants, where large machinery is installed and manufacturing traditions are set. In any industry, when new contracts are awarded and new production plans are developed, the firms must decide whether to build new greenfield plants or renovate existing facilities.
plants or use existing ones, perhaps with modifications. New plants may be more expensive to build, but they can be designed to maximize the efficiencies from the most up-to-date production processes. One company took a second look at a planned new facility and was able to reduce the space required by two-thirds. Building a new line in a brownfield plant means that “monuments” built for some other program may have to be “worked around” for the new program.

This issue arises in the manufacture of composites because of the largest of the “monuments” used in the production of composites, autoclaves. Autoclaves are large chambers (shaped generally like cylinders, up to 40 feet in diameter) where high temperature and pressure can be applied to cure composite parts. In plants with existing autoclaves, production flow must be planned around these autoclaves to maximize flow, given that the curing process must occur at a particular place in the plant, unless significant investment is made in moving the autoclave. The necessity to cure parts in an autoclave can provide a constraint on lean product flow. A related issue is that monuments, such as autoclaves, are often built for large capacities so the largest parts can be cured inside them. To use them efficiently for smaller parts, large batches are cured at one time. (The operating expenses of autoclaves stemming from enormous energy requirements generally mean that parts that need to be cured build up until an autoclave-sized batch is developed.) However, the lean manufacturing philosophy is built on small lot sizes that flow quickly through the plant with minimal time spent in non-value-added activities, like queuing for the next process. Thus, regardless of a company’s commitment to lean, physical monuments are always a constraint in brownfield situations.

**Summary of Typical Savings**

The following results summarize reports by military aircraft companies of savings from a sample of their efforts toward improving manufacturing processes:

- In a sample of 20 “leaned” cells and production areas, direct labor hours used to produce parts after lean principles were incorporated into production declined between 5 percent and 81 percent, with an average of 36 percent.
• Cycle time to produce parts was reduced between 13 percent and 93 percent (average 44 percent) (15 data points)

• Floor space savings ranged from 0 percent to 61 percent (average 24 percent) (12 data points)

• Part travel was reduced between 25 percent and 95 percent (average 61 percent) (10 data points)

• People travel was reduced between 23 percent and 94 percent (average 55 percent) (9 data points)

These averages should be considered suggestive rather than as offering a definitive result. Critically, the scales of different savings initiatives are unknown. Companies did not frequently offer information on the size of the effort, so it is difficult to know if a 50 percent reduction in labor meant the elimination of 1 job or of 20. The data suggest an inverse relationship between the size of the effort being leaned and the percentage savings, i.e., smaller pilots tended to yield much larger savings. Hence, analysts should use extreme caution when scaling up savings estimates from smaller pilots to the entire production process. In addition, savings in cycle time for noncritical path parts or subassemblies may not yield overall product cycle time reductions.

Because it is much more difficult to scale up lean production across cells than to lean out small production areas, it is impossible to assess the savings from lean manufacturing across the plant or enterprise by looking at these initial, suggestive results. Integrating lean across an entire factory floor presents many challenges that have not yet successfully been addressed in the aircraft industry. A more definitive assessment must wait for more complete data.

Furthermore, there exists the possibility of two kinds of selection bias in the reporting of these experiments. Companies may have selected their least efficient production areas to be leaned out first. This “low hanging fruit” would produce larger savings than the typical cell. Second, companies may have been biased toward describing their most successful efforts. There are no guarantees that the sample of lean areas they offered represented their most typical results. Unsuccessful efforts probably were not reported, not necessarily in any attempt to deceive or shade the results but because attention
within companies is focused on efforts with positive outcomes, while projects that do not work are pushed aside and quickly become orphaned. Corporate focus on negative outcomes is productive when it captures lessons learned that can be used to make other efforts more successful, but this does not always take place.

That said, these results indicate that incorporating principles and tools of lean manufacturing has the potential to reduce costs in aircraft production. For reasons described above, applying any kind of a macro lean credit to a historically based CER cannot be analytically supported. Giving lean credit for the mathematical average of results of selected pilot cases reported by the companies is very likely too generous. A more conservative savings estimate of under 20 percent when lean principles are totally implemented throughout a plant is more reasonable but is not based on analytically derived evidence. However, whatever savings are experienced in the future will not come without significant effort and attention from company management and without a combination of incentives and pressure from the customer.