# Lean Aerospace Initiative Electronic Sector Study


by

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## Abstract

A study was conducted under the auspices of the Lean Aerospace Initiative to examine electronic component manufacturing in the aerospace and defense sector. The purpose of this research was to understand how current manufacturing systems are designed and managed, as well as to examine the sources of increment to production throughput.

Six programs of varying complexity, volume, and types of application were studied at five different sites. Data were collected through interviews with site personnel and from standardized reports on production, quality, and other general metrics. These data were analyzed to determine the most common reasons for perturbations in the production systems as well as , to understand what aspects of the manufacturing system design affect the frequency and impact of these disturbances.

Results showed that material availability and component quality are the leading causes of delays in this manufacturing sector. This information has numerous implications on how systems should be designed to mitigate these throughput disturbances. These applications are also examined in this paper through a documentation of some effective practices observed at the sites studied.

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## Acknowledgements

It is now June of 2000. It was then, June of 1986, when I, as a boy at the age of 14 growing up in the inner-city of Chicago, became fascinated by a display of ingenuity and determination that was shown on a public television special on students competing in MIT's, now famous, 2.070 design competition. Since then I have dreamed of being a part of this marvelous institution and it will be some time before I fully believe that this lifelong goal is finally accomplished.

My deepest appreciation goes to my beloved mother Lucia Roman who instilled in me the value of an education, and to my sister Betsabel Roman for her unflagging support. Thanks also to my research director, Tom Shields for his guidance though the gray matter that is research, and to the numerous people in the participating sites and the Lean Aerospace Initiative Manufacturing Systems Research Team, without whom this study would not have been possible. But above all I must thank God for the countless blessings He has bestowed upon me and for walking with me through all the challenges of my life. Every day is a constant reminder of the immortalized words of a personal hero, United Farm Workers founder Cesar Chavez, who truly believed that "Si se puede", *it is possible*. Let no one tell us different.

- Marco Antonio Roman

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# 1. Introduction

## *1.1 Project Description*

The Lean Aerospace Initiative (LAI) was formed with the intention to understand better the challenges and opportunities that Aerospace and Defense manufacturing face and to transfer the practices of lean manufacturing to this unique context. Such an effort requires examination of the entire Aerospace and Defense supply-chain, an integral part of which is the actual production system. Consequently, the Manufacturing Systems Research Team (MSRT) within LAI initiated a study into the design and management of complex manufacturing systems. This was a three part study established to examine the manufacturing systems in three major sectors of aerospace production: Engines, Airframes and Electronics. This paper examines the third of these categories by studying the manufacturing systems of electronic components (EC's). The paper begins with a discussion on the background of the study, and the methodology used, then follows with a description of the electronics sector, and the findings from this research, and finally, looks at some of the system differences, best practices and comparisons with the Lean Enterprise Model (LEM).

## *1.2 Background*

The term "lean" was originally coined by the International Motor Vehicle Program at MIT, to provide a US automotive manufacturer-friendly name for the Toyota Production System [Womack et al., 1990]. The term itself however has become amorphous, so much so, that it has become difficult to get a consistent definition of this system from even those who would claim to know a substantial amount on the subject. However if we look towards the Japanese founder of these methods I think we can find the clearest and most simple description:

"The Toyota production system strives to eliminate all waste"[1]

- Taichi Ohno

[1] Robinson, 1991

If one accepts this to be a reasonable definition, then it becomes difficult to imagine an industry in which the principles of lean manufacturing as described by its creator, could not be applied. The challenge for the aerospace industry is that some of the applications of lean manufacturing that have been developed in the automotive industry are difficult to transfer, because they have been made around a completely different system with very different requirements.

Aerospace consortium members have expressed a desire to learn how to design and manage a lean manufacturing system from what has been traditionally considered a craft production system. An issue of primary interest in this realm has been to understand what are the important enabling practices in reducing the cycle time to produce a product. It is for this reason that this study was undertaken, the goal of which was to identify those systemic factors that affect manufacturing performance. For this study, performance would be primarily measured through: performance to schedule, product throughput efficiency, and process flow. Consequently, a critical dimension of analysis will be delays in the flow of production, where delays are defined as disruptive events in a system which detrimentally effect one of the stated performance metrics.

In total five manufacturing sites were involved in this study. At each site considerable time was spent gathering data on various aspects of production delivery performance, throughput times, quality, and reasons for delays, amounting to hundreds of data points, which were used for the analysis of this sector.

### *1.3 Methodology*

The basis for this project was discussed by the MSRT and electronic sector consortium members via LAI plenary sessions, teleconferences and emails. As alluded to in the background section, the interest originated in the beginning of the LAI Phase II, through a desire on the part of aerospace manufacturers to understand how to design and manage lean manufacturing systems with an agreed upon research focus on how to control and reduce cycle time.

Consortium members were asked to identify potential sites and products that could be studied. Once various products were submitted, the members were surveyed for product selection criteria, to help ensure a representative sample of products for this sector. Virtually every component of an aerospace or defense product is in some way or other composed of electronic components. Consequently one of the first steps we took was to try and focus our study by establishing a range of products that could be similar in some respects and thus have a basis for the comparison of their manufacturing systems. LAI consortium members were asked to submit lists of potential components for this study. Based on the variety of products that were received, a band was drawn around two factors, agreed upon by electronic sector MSRT members, that could be used to narrow the variety of products. These two characteristics were production volume and product complexity as described by part count. A preferred set of volumes and part counts were chosen based on selecting the products within a fixed range from the median of those candidate products submitted. This resulted in a part count range of 1500-5000 total components and volume range between 5 and 500 units per month. This also allowed for some comparison between those manufacturing systems used for very low volume production and those that approached more commercial levels of volume, and could assist in determining the characteristics that define these different types of systems.

Given this input, five programs were chosen at five different sites. A sixth program was later added which fell outside the selected range of product volume and complexity. It was included since it was an opportunity offered by an already participating site that required little additional effort and could serve as a contrast to the other programs that were studied.

## 2. Electronic Component Assembly

### *2.1 Category Description*

The types of products ultimately studied varied widely in application from radio signal generators to ballistic combat systems. The basic configuration of this set of products, however, is fundamentally similar. Ultimately all electrical components are a series of circuit boards assembled with different input, output and control devices within one or several housings. The typical product chain is illustrated in Figure 1.

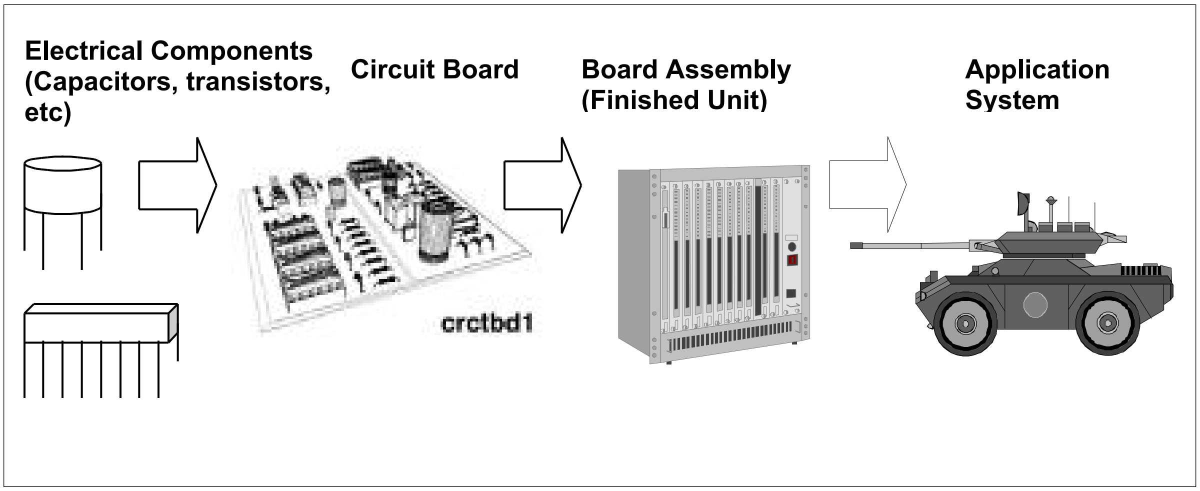


**Figure 1: Example product hierarchy**

*2.1.1 Circuit Boards:*

Circuit Boards, or boards, as they will be referred to in this paper[2], consist of a series of electrical components that are mounted or inserted onto a resin motherboard and secured through some form of soldering process. These subassemblies are of course the most fundamental component of any type of electronic assembly from the first tube radio ever produced to modern day satellite components. These subassemblies typically make up the largest portion of a product's total part count, up to 85%, and are often the core technological components of a final assembly. For this reason circuit board architecture was often considered confidential material and the source of some competitive advantage in this sector. The number or circuit boards used in a product varied from program to program in this study. Figure 2 shows examples of actual circuit boards.

[2] This paper will use the terms "board" or "circuit board" interchangeably to describe a unit which is completely assembled with its electrical components, unless otherwise specified.

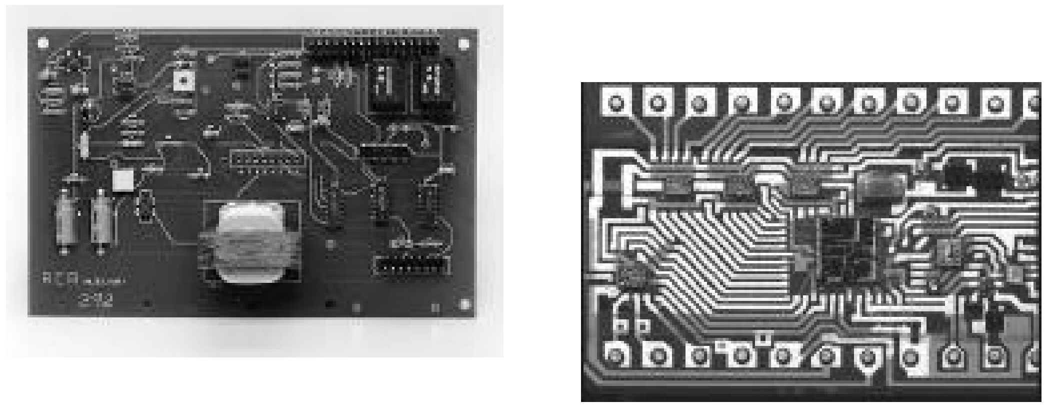

**Figure 2: Example Circuit Boards**

*2.1.2 Final Assemblies*

A final assembly can take on various forms in the companies that were studied. In one instance it consisted of a standard rack unit, much resembling a box that was used for field repairs of engine control units. This unit was essentially a series of circuit boards, assembled with input and output connectors installed in a robust casing system. In other cases the final assembly unit was a subassembly that would be used in an armored vehicle assembly facility or a subassembly that would be fitted with munitions and a housing to form a ballistic missile. In these instances the electrical componentry included optical sensing and processing equipment, electromechanical servo motors to control various component movements, and communications systems.

*2.1.3 Programs Studied*

The products in this research varied in volume, complexity and applications. Table 1 shows a general description of these attributes as well as other relevant product characteristics.

- *Total Parts per Assembly* includes all components in every subassembly of the relevant program.
- *Study Site Assembled Parts* is the total number of parts which are assembled in the production area that was studied for each program.
- *Volume* described the average number of units produced per month.

- *# of Operations* is the number of process steps executed at the participating site during assembly. This was calculated using the routing sheets collected for each program.
- *Program Maturity* describes the number of years since the inception of the program or the last major redesign, whichever is less.

The variety in the programs studied was unique to this sector, as compared to the engine and airframe sectors[3]. This factor both enriched and complicated the analysis required to extract meaningful information and conclusions that would be relevant not only to the manufacturers of these types of products but to those producers of many other electronic component categories as well.

| ***PROGRAM:*** | **A** | **B** | **C** | **D** | **E** | **F** |
|---|---|---|---|---|---|---|
| *General Description* | Frequency Generator | Control System | Ballistic System | Ballistic System | Optical Combat Hardware | Airplane Generator Control |
| *Total Parts per Assembly* | 800 | 3000 | 373 | 1800 | 478 | 1393 |
| *Study Site Assembled Parts* | 17 | 1158 | 58 | 75 | 45 | 1393 |
| *Volume (Units/Month)* | 100 | 5 | 500 | 120 | 15 | 60 |
| *# of Operations* | 24 | 140 | 150 | 71 | 20 | 51 |
| *Program Maturity (Years)* | 10 | 12 | 5 | 15 | 2 | N/A |

**Table 1: Study program descriptions**

[3] A reference to the programs studied in the graduate theses of Ramirez 1998 and Wang 1999

### *2.2 Electronic Sector Manufacturing Elements*

There are three distinct manufacturing steps that exist in the general production of electronic products: Circuit Board Fabrication, Unit Assembly, and Testing. Although a vast simplification, these elements form the production common denominator of this sector. They do not, however, always occur strictly in that sequence. Often times there are various stages of assembly, as well as various phases of testing throughout the manufacturing processes, and almost always at the end of production in the form of some final acceptance testing. This final testing is most common to those systems supplied under government contracts. There are of course countless different types of other assembly operations involved in this sector which can vary with the type of product being produced and the application environment. The challenge for us was in isolating the electronic manufacturing systems' characteristics despite these process variations. Figure 3 illustrates a typical process flow for the products in this research.

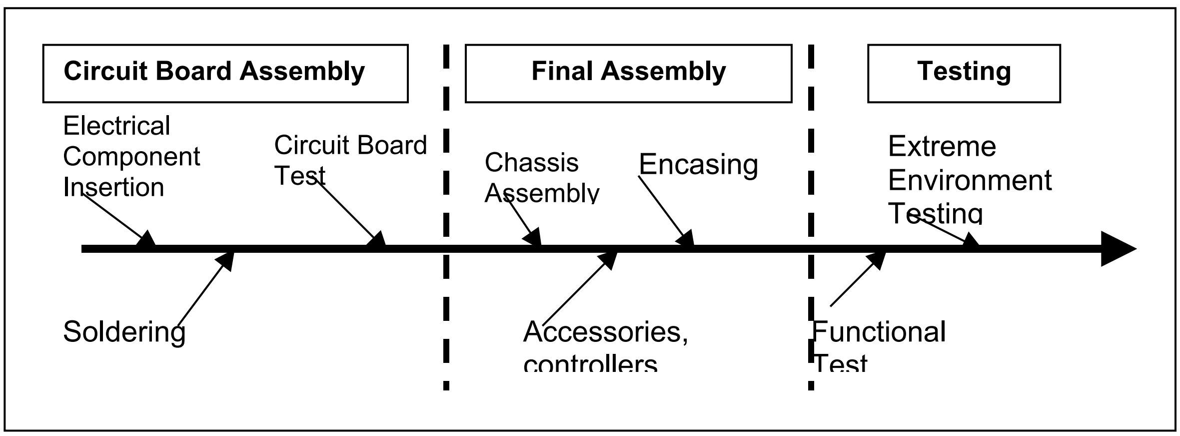


**Figure 3: General process map for electronic component assembly**

*2.2.1 Board Fabrication:*

There are primarily two methods used in the manufacturing of Circuit Boards: through-hole and surface mount. Through-hole manufacturing is the more mature technology which mounts and inserts the leads of electrical circuit components through a thin plastic resin board which is pre-designed with the proper locations, slots, and connections. These components are then soldered securely on the underside of the board through an automated or manual soldering operation, or a combination of the two. Surface-mount boards use a more recent technology in which components are placed on the surface of an empty board. These components are then interconnected through a wave-soldering process that precisely lays soldering material with a pre-designed template, which is subsequently heated. Many boards will use a combination of these two technologies in a manner that optimizes circuit board performance and cost requirements.

*2.2.2 Unit Assembly*

The majority of operations in this sector occur in the unit assembly area. This is the area that was most in common among all sites. Although the types of circuit board manufacturing and testing varied between facilities, all sites had unit assembly areas that were surprisingly similar in their configurations and methods of operating. Product assembly areas are typically configured either as an assembly line or as a set of workstations that perform parallel operations. Assembly lines are common in personal computer manufacturing and other products that have high volumes and require significant manual operations. Workstations are more common in lower volume manufacturing and “job-shop”-type production for their increased flexibility. All the defense sites in this study used a workstation arrangement for their assembly operations.

Every facility used some form of a kitting system for assembling units. A kit was a prepared set of components that were needed for the build of one, or more than one, units. When an order was released, the first operation would take place in a materials area, typically referred to as a materials crib, where most of the raw materials inventory was kept. A person, typically from that area, would then gather all the components necessary to assemble the type and quantity of products on the order and place the materials in one or several containers (usually one container per unit being built). These kits would then be transported to an incoming materials staging area at the appropriate assembly area.

*2.2.3 Testing*

The third major component of EC manufacturing was testing. Testing could occur in various steps throughout the process, but almost always included a final acceptance test for a finished unit.  The degree to which products were tested varied significantly from site to site.   Testing requirements were often outlined by the customer, particularly in defense contracts. There are typically testing points after a circuit board is completed and sometimes through out the assembly processes.  The types of testing conducted could vary from simple continuity test to full functionality tests in extreme environmental conditions and a range of mechanical durability tests.

Product testing was a defining manufacturing characteristic of this sector.  Due to the expensive nature of test equipment, and the low volumes produced for any one program, testing hardware was typically a resource that was shared by many programs, although there was some equipment that was unique to a program.  Another unique situation was the stringent testing requirement in this sector, testing was often a relatively long operation that required extensive, setup and documentation.  Many tests required a lengthy soak period or cycle time. Consequently this operation was often a bottleneck in the EC production process.

## 3. Findings

### *3.1 Typical Plant Configuration*

The EC manufacturing facilities visited for this study were similar in layout design. Typically, there were clearly separated and demarcated areas for each of the production processes of assembly, testing and circuit board production (where applicable).  Figure 4 below shows a representation of a typical layout, which includes some areas not present at all, locations such as a local warehouse, and packing area.

Flow of material was smoothed where possible but material transportation was not observed to be a priority, unlike other industries of manufacturing.  This was most likely due to the low volumes involved and the relative ease of physically transporting the products in this study, since most of the finished units were less than 40 pounds in weight.  Often, shared resources such as oversized testing equipment were located in another room due to weight constraints or the controlled environments required for some types of testing.   Typically, there was also an area for support staff located adjacent to the production area.

Although every site used a workstation arrangement for their assembly area, program C had only recently switched to using workstations from a previous assembly line arrangement.  As a result, this program cited improvements in performance through reduced work-in-process inventory (WIP), as well as increased process ownership and accountability on the part of the operators.  The improvements realized from this change are shown in Figure 5.

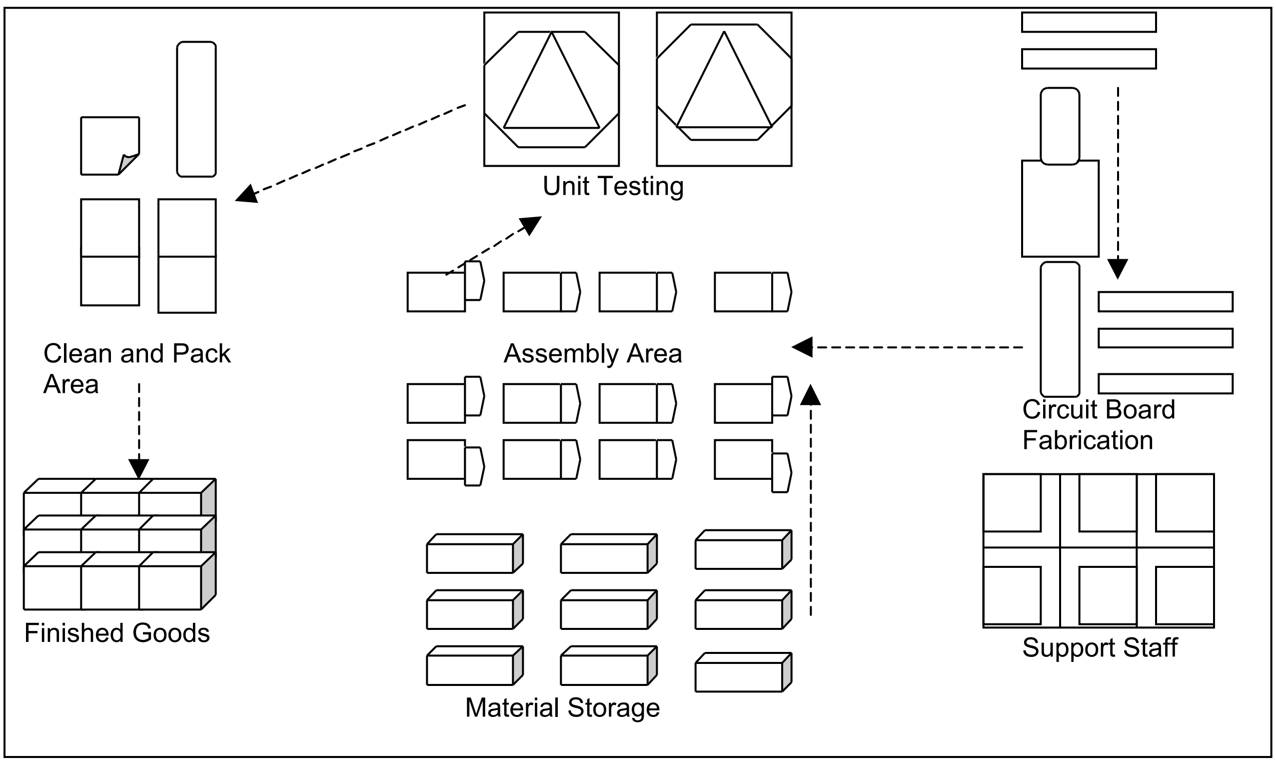


**Figure 4: Example factory layout and Flow**

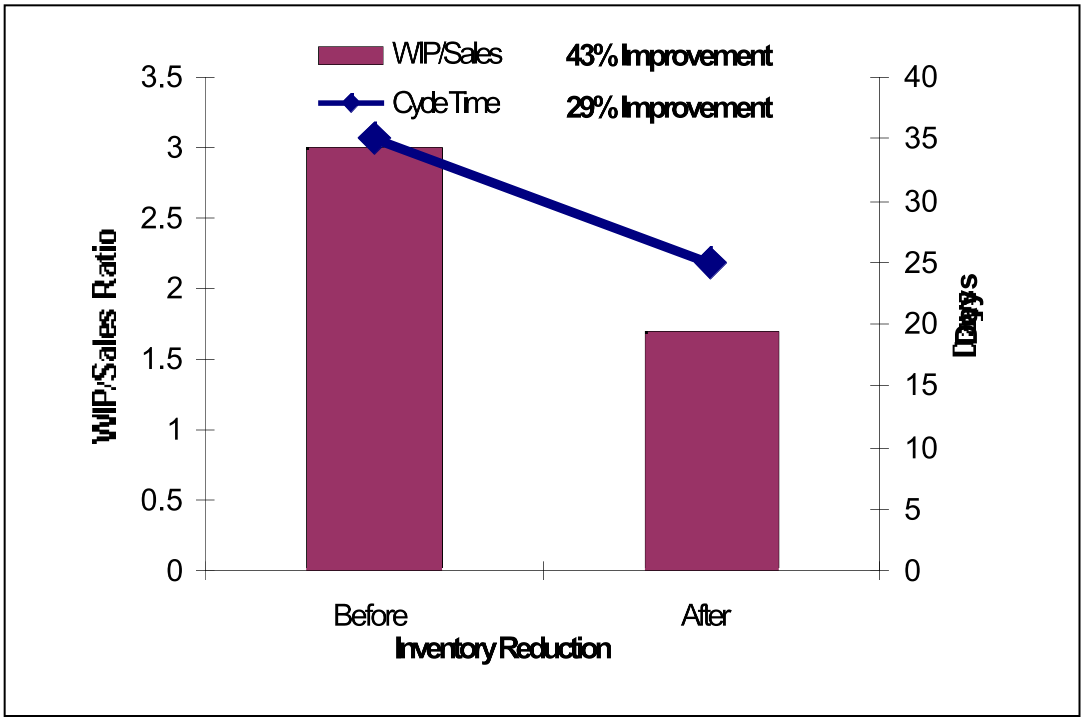


**Figure 5: Program C WIP reduction effect**

### *3.2 Sector Description*

*3.2.1 Program Descriptions*

Before discussing performance with any depth, it is important to get a basic understanding of how this sector operates compared to other manufacturing environments. One way to get a frame of reference is to examine some common manufacturing metrics such as, On Time Delivery, Planned Build Times, Order Stability, Value Added %, and Inventory Turns. Although looking at these metrics alone does not determine how good or poorly a system is operating, it serves to provide a soft basis for comparison, with other sectors and industries. Table 2 shows the data for the six programs on these measures, which are described in further detail in the paragraphs that follow.

| PROGRAM: | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| *On time delivery* | 83% | 100% | 100% | 100% | 83% | 87% |
| *Planned build time (days)* | 3 | 28 | 25 | 9 | 9 | 14 |
| *Value-added percentage* | 9% | 10% | 8% | 10% | 14% | 8% |
| *Inventory turns/ year* | 7 | 3.3 | 6 | 6 | 3.5 | 2.5 |
| *Days prior to delivery of 90% firm schedule* | 60 | 90 | 270 | 270 | 180 | 90 |

**Table 2: Sector descriptive metrics**

On time delivery to external customers was generally favorable in the electronics' sector, ranging from 83% to 100% of delivery's that were made on the dates committed. On average the defense sector, within electronics did better on this metric than the commercial side. But there is an important element to take note of here. On time delivery to the customer does not mean that flow within the operations of the producer is in order. Actually, data from this study showed that there is little correlation, for example, between timely delivery to the customer and the timely movement of material within a production operation. This is demonstrated in Figure 6. In this diagram customer on-time delivery performance is plotted against internal on time percentage, which is a measure of the accuracy in meeting MRP schedules within each of the internal operations of the process studied.

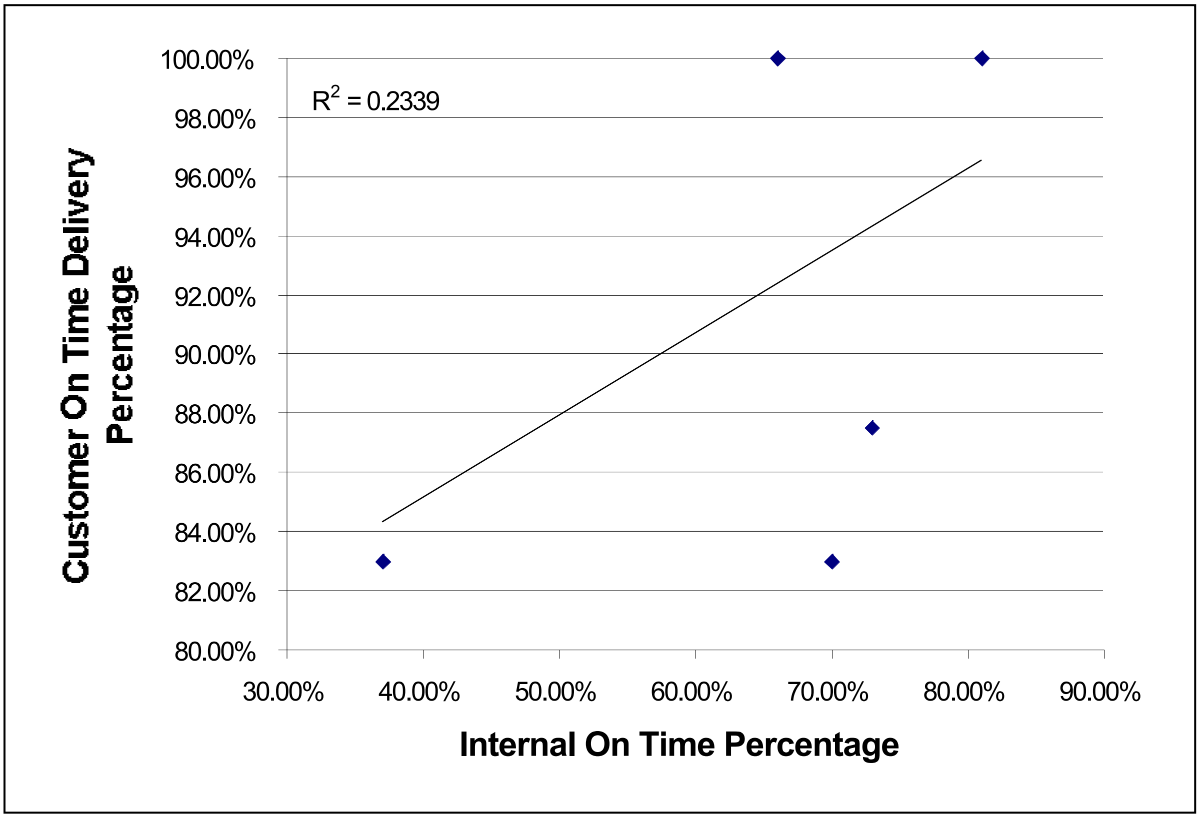


**Figure 6: On-time delivery vs. MRP performance**

One reason this type of disparity can exist between external and internal delivery performance is because lead times can be padded significantly to reduce the risk from perturbations within the operations of the producer. Figure 7 shows the ratio of actual build times to planned build times, and one standard deviation about the average.

As this chart illustrates, there is a very wide range in cycle time performance. An interesting observation is that those programs which had the best on time delivery performance in the defense sector, also had good cycle time performance in this chart (actual/planned build ratio less than 1) with the least variance. One exception to this was program B, which achieved excellent external delivery performance despite having actual build times that exceeded those planned. A reason for this may have been because program B also had close to twice the level of inventory than that of programs C and D, indicating a potential additional buffer between that site and its end customers.

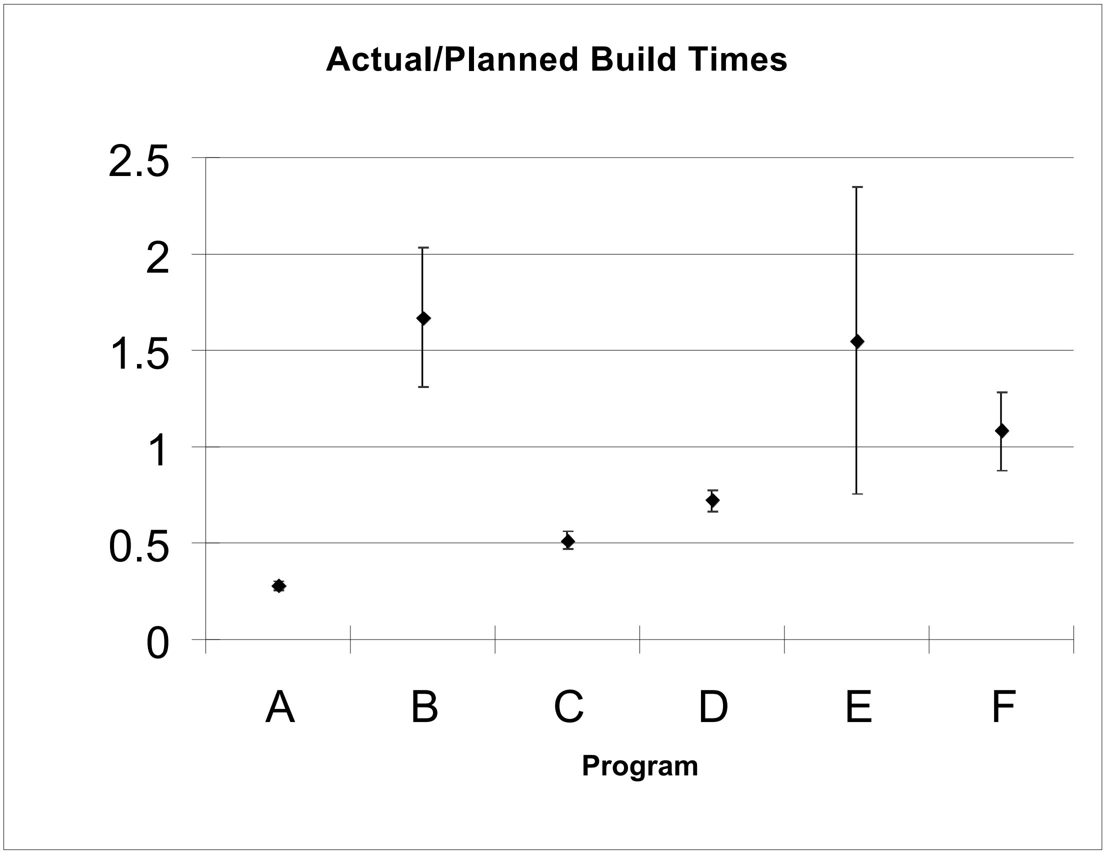


**Figure 7: Cycle time performance by program**

Further examination of cycle time performance showed that those sites which had better MRP performance also tended to have less variation in their cycle times. This relationship is illustrated in Figure 8 and supports the importance of order in the internal operations of a factory as rather than relying solely on average on-time delivery, to measure overall effectiveness.

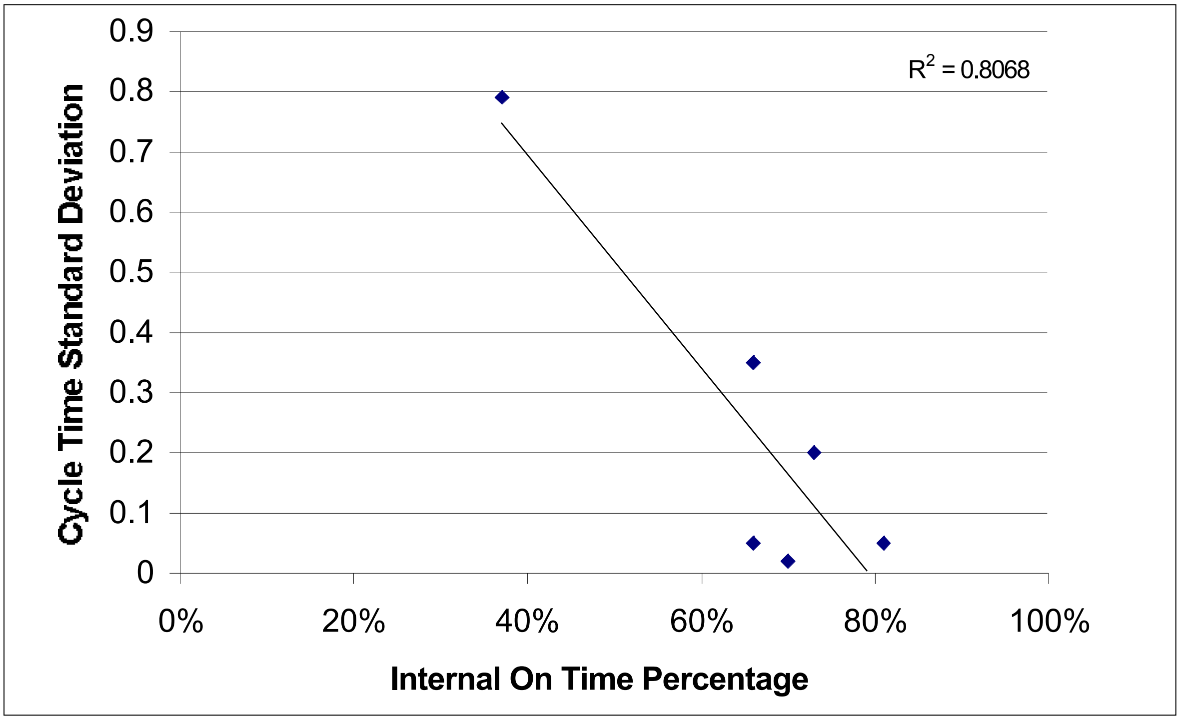


**Figure 8: Cycle time variation vs. MRP performance**

The commercial programs, A and F, posed some interesting comparisons. Program A had the lowest actual/planned build time ratio. It was observed, however, that there was a significant amount of cycle time buffer incorporated into the schedules of this site. Planned cycle times across all the programs in this site averaged about 3.5 times the actual cycle times. This presents a potential compromise of perceived responsiveness for Program A, if customers are being quoted order lead times based on a cycle time that is 3.5 times longer than reality. Program F, on the other hand, partially measured its performance based on the accuracy of its planned cycle times. This incentive was reflected in the proximity to the value of 1, of their actual to planned ratio. What is more important though, than mean actual-to-planned times, is the variability within the production systems of these programs, and in this respect, both programs A and F are good performers.

The measure of *Value-added percentage* is an estimate for the flow efficiency of a product. It measures the actual time a product is worked on, as a percentage of its total cycle time. The time spent by certain products in testing and curing operations is included, although with different customer requirements and/or with technological developments these operations may not be necessary and could be considered non-value added as well. Although this measure may be partly affected by the batch size used for a product (since no product can be more efficient in this metric than 1/[its batch size] ), it would only be a small percentage of the total time involved for the products in this sector. In addition the measure can have value with the additional comparison to the ideal scenario of a one-piece flow.

*Days prior to delivery of 90% firm schedule* is an estimate of order stability. Production managers at every site were surveyed on how many days in advance of a delivery date do they have confidence that 90% of their schedule is firm. For example, if a firm has an order for 100 units of program X with a delivery due date of June 30$^{th}$ , and they are confident as far in advance of January 30$^{th}$ that this order will not change by more than 10%, then this firm would receive 150 days for this metric (June 30$^{th}$ – January 30$^{th}$). However, if instead they, on average, do not have confidence to stay within that order volume range until May 30$^{th}$, they would receive 30 days for this metric.

### 3.2.2 Planned Build Times

In the engine sector study there was a relationship found between the total number of parts and the time expected to complete the assembly. However, in the electronics sector this relationship did not exist, as is shown in Figure 9. The reason this is believed to be the case is that the total part count can be largely biased by the number of components on the different number of circuit boards used in these products. The installation of circuit board components can consume relatively little time in a single automated operation but contribute greatly to the total part count. This is typically not the case in an engine assembly or other largely mechanical products.

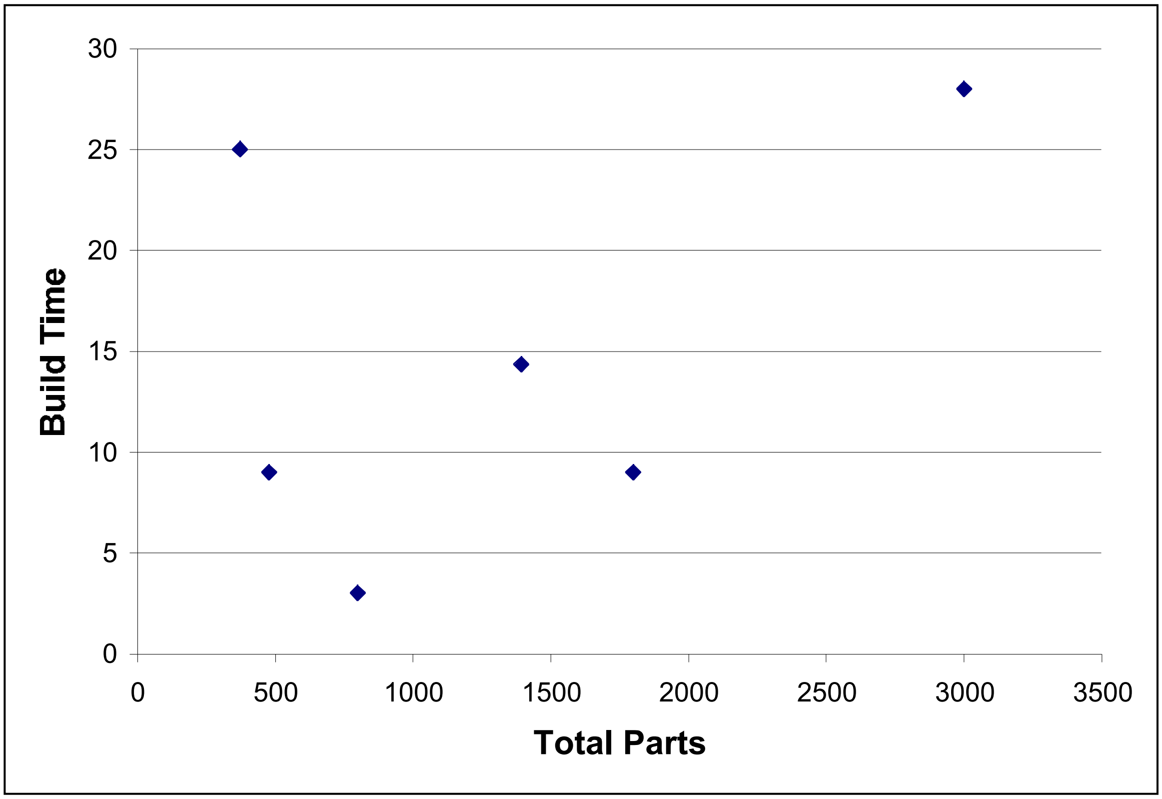


**Figure 9: Build time vs. Product complexity**

However, another relationship which is more sensible in the general case, was demonstrated in the electronics sector. There was a moderate correlation with the *number of operations* and the expected build time for a product. Figure 10 illustrates this relationship for the programs studied. The number of operations for each program was extracted from the corresponding process sheets, which shared a similar level of complexity in operational detail. The demonstrated relationship is reasonable because, given the similar nature of the processes examined (board fabrication, assembly, and testing), it would be reasonable to think that the time varies with the complexity of the process rather than the complexity of the product.

Although the extreme variety of programs in this sector makes it difficult to compare across all sites, there were indeed some characteristics and trends specific to the entire electronics sector that were observed and documented. In addition, we compared the differences in similar production systems and looked at how changes within a site, affect production performance. In this manner the applicability of this study can be relevant for various types of electronic manufacturing since it will examine the behavior of production system changes and not of program differences.

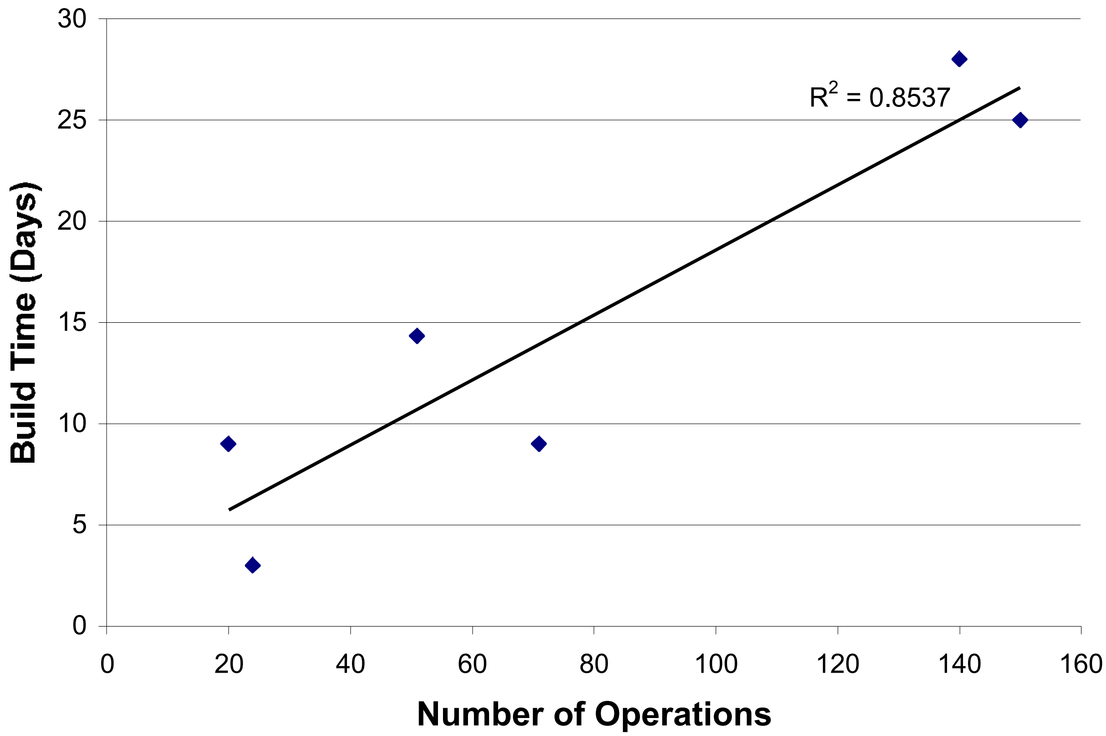


**Figure 10: Build time vs. Process Complexity**

### *3.3 Scheduling and Production*

There were essentially two ways in which production orders for a company were determined. One way was by determining these orders off of a long-term contract, which was common for government orders. These contracts were usually for a one-year period and were typically renewed at the end of the term. Contracts would have delivery quantities and dates estimated for the contract period. As a result production schedules had few fluctuations as they were established well in advance of delivery due dates. A typical system of this type is shown in Figure 11.

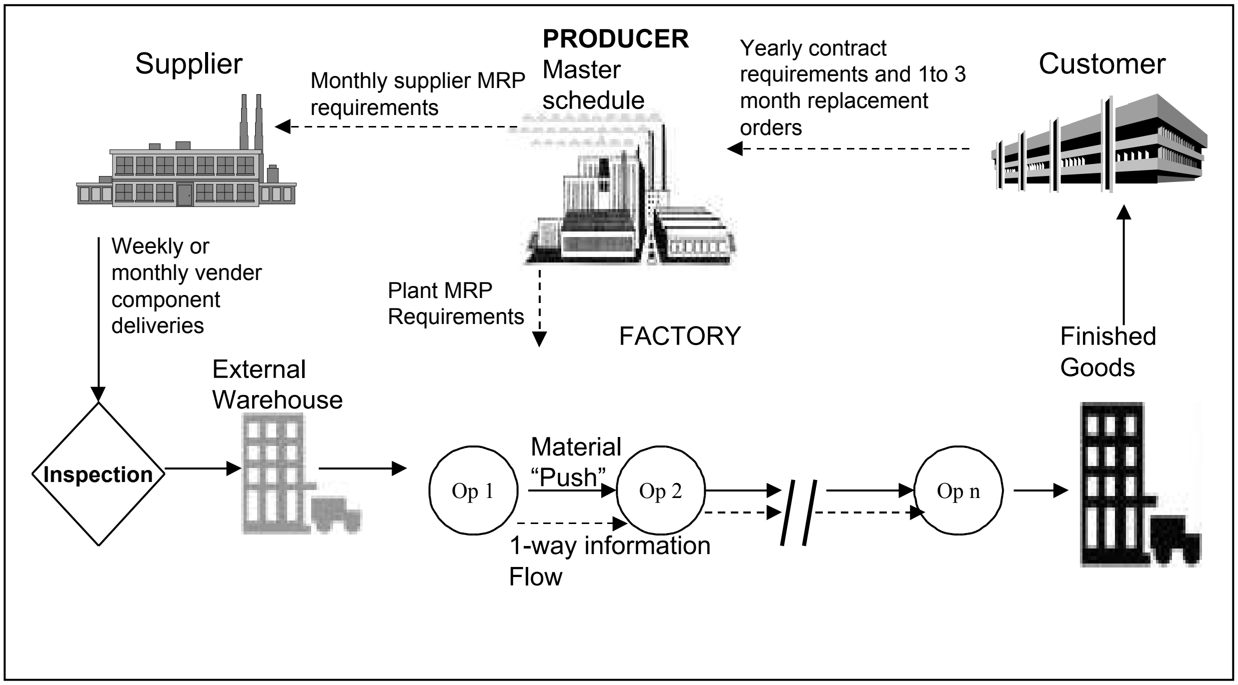


**Figure 11: Typical defense manufacturing system**

The second method, which was more common for commercial manufacturers, was production orders based on individual customer sales or short-term contracts. This is often the situation for commercial manufacturers, although not always, as it depends on the application and customer preferences. Products that are used as a subsystem on commercial aircraft have a much more stable demand than those systems that are used as final products, such as in the case of a stand-alone radio unit. Figure 12 is a diagram of this system.

The production orders in this latter environment experience significantly more volatility, and are often based on regularly scheduled forecasts. As a result there is less certainty in the production schedule. This variation is reflected in Figure 13 which shows the days to 90% firm schedule metric together with the sector in which the program operates and the method of scheduling (between build-to-orders and build-to-forecast).

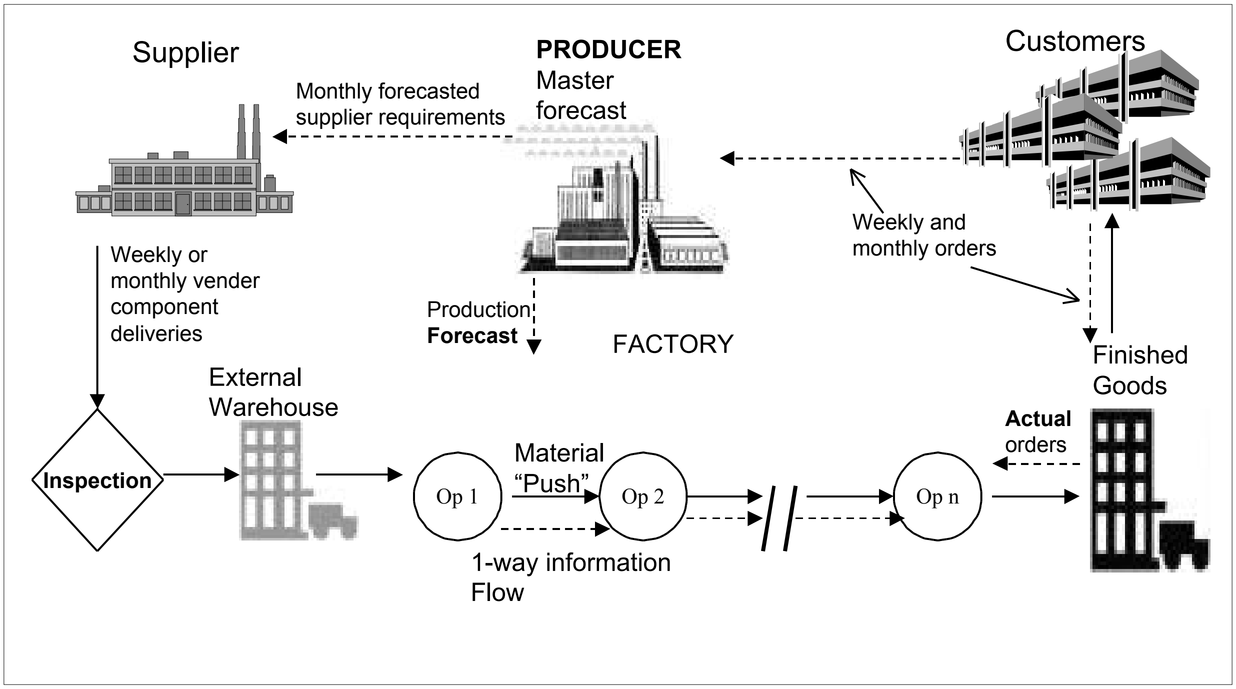


**Figure 12: Commercial forecasting manufacturing system**

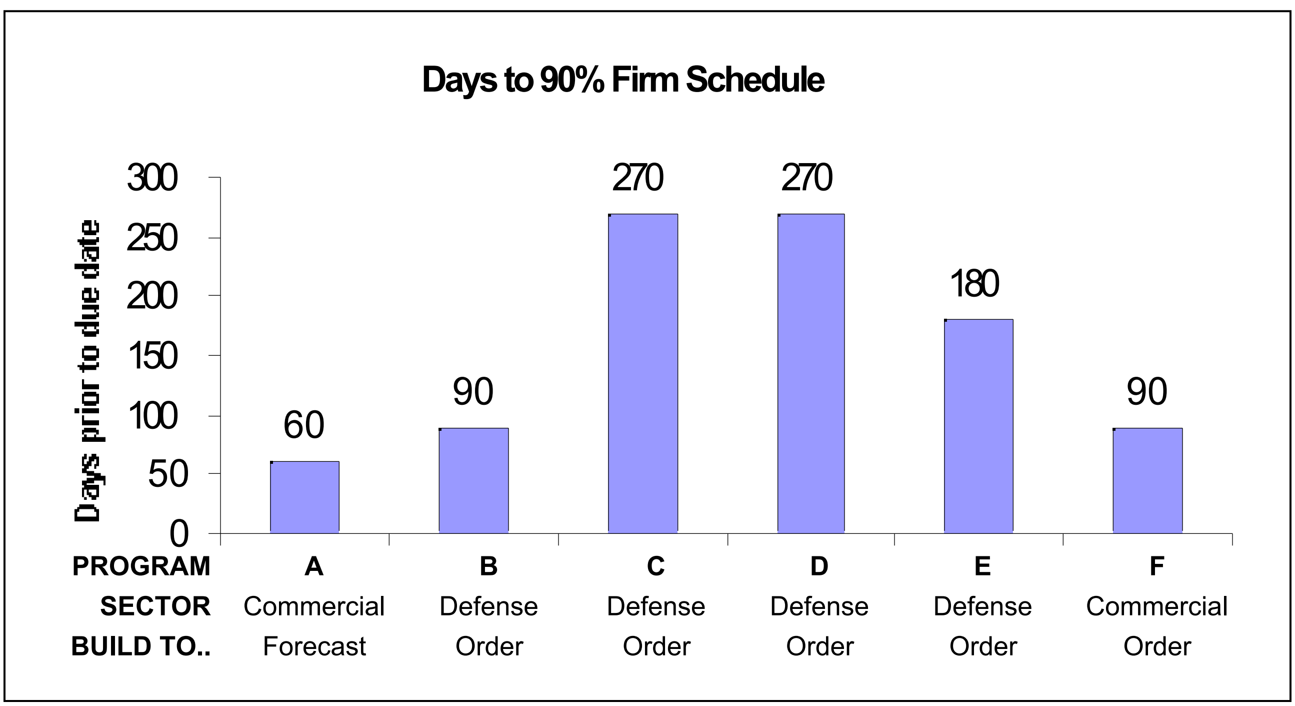


**Figure 13: Scheduling characteristics by program**

As this chart shows, the average confidence in schedules was, on average less for the commercial sector than for defense. In addition, the site, which built to forecast, had the least amount of certainty in their production requirements in this study. Program B showed a significantly lower confidence in their scheduled than their other defense contracting counterparts. The reason for this was that its production requirements consisted of a large component of replacement units, the quantities of which could not be determined far in advance. This caused an additional factor of uncertainty in the number of units that would be requested from production.

Every facility in this study used some version of a material requirements planning system (MRP) to manage their purchasing and order requirements. Internally these orders were communicated to a production manager who would allocate resources accordingly and work with a floor supervisor to schedule the production of an order in her or his area. It was in this "push" method that programs A, B, E, and F operated.

Programs C and D, which were produced in different areas of the same facility, were different in two ways with respect to production strategy. First they implemented a "pull" production management systems. Factory floor requirements were regulated through the use of a 3-bin kanban system. This system is illustrated in Figure 14. Every operation had 3 kanban containers assigned to it. One would be at the operation, one at the customer operation and one in transit. In this manner an operation would produce if it had a kanban container in which to place product. The production manager would change the quantity permitted per container based on order requirements for a given time period at the internal customer for these factory areas.
One reason this site could execute a kanban work management system well was that, unlike any other facility in this study, it had single-product, dedicated factory areas. All other programs were manufactured in multi-product areas. This arrangement is more feasible for programs C and D because of their relatively large volume. However, this variable alone does not imply that this is the best configuration. Site A also had higher than average order quantities for this study, yet used a multi-product factory floor. In addition, programs C and D used a local warehouse configuration in which inventory

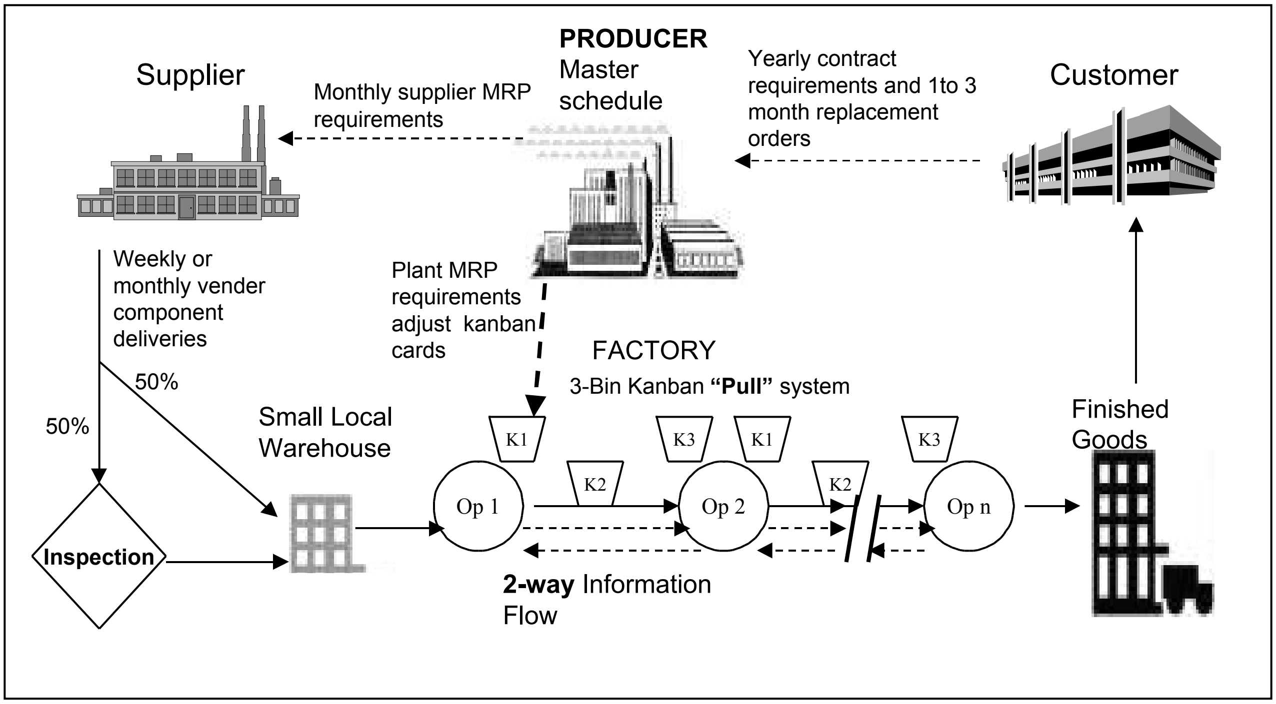


**Figure 14: Manufacturing system at programs C and D**

was brought directly to the point of use instead of storing it in a separate warehouse. If this inventory was from a certified supplier it did not have to go through incoming inspection. As a result, this site was able to significantly reduce inventory, storage space and dock-to-stock cycle time.

### *3.4 Reasons for Delay*

We have stipulated from the beginning that the hindrance to throughput, the focus of our research, is delay in the production system. Delays can occur anywhere in the supply chain and we carefully examined the sources of these delays to understand in what ways they manifest themselves and how a manufacturing system can be designed to minimize these. The commercial and military sectors demonstrated some unique differences, which were intrinsic to the environment in which they operate. Consequently, we will look at each of these separately, examining first the commercial side, then military and then summarize with some conclusions on this data. The data were collected over a six month period from various reports produced at each of the participating sites. The reports included daily or weekly production reports, as well as delay and schedule performance reports that were generated either through MRP systems or through manual production floor record keeping.

### *3.4.1 Commercial*

Of the two commercial programs involved in this study, one supplied a single airline manufacturer and another had multiple customers in numerous industries. This supply-chain structure had a significant impact on the sources of delay for this sector. Figure 15 shows the reasons for delay according to the reports gathered at the respective sites.

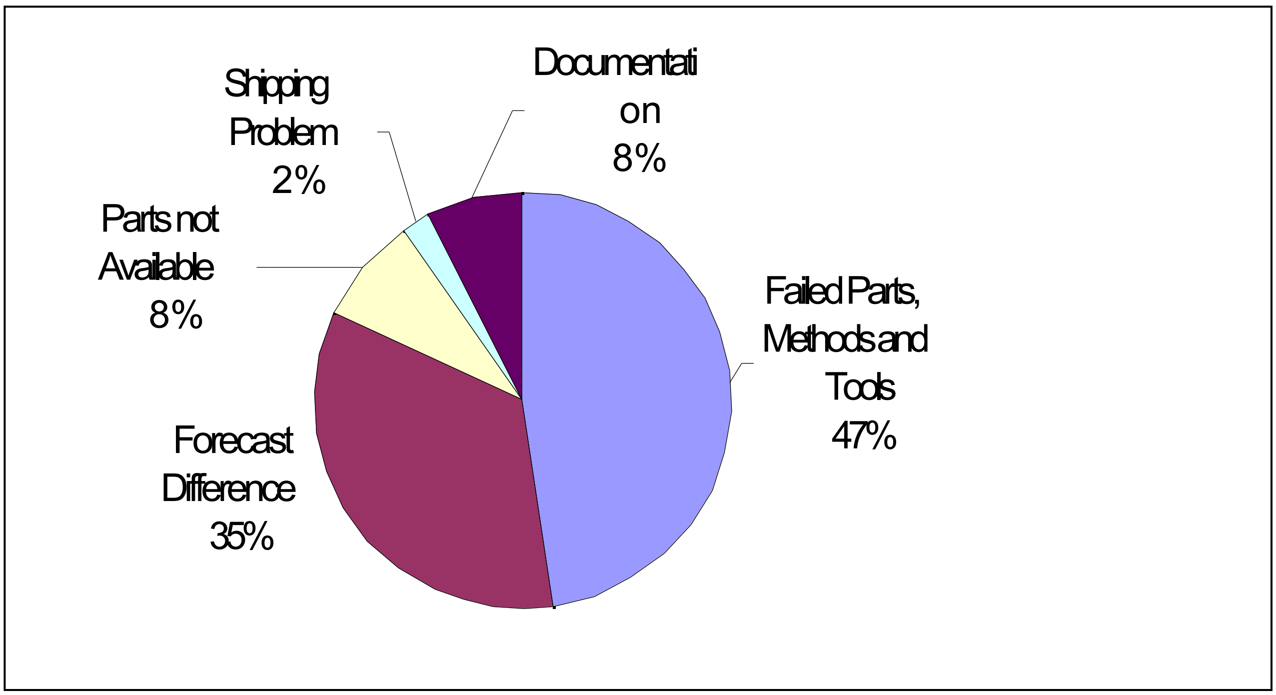


**Figure 15: Reasons for delay in commercial sector**

As the chart shows, the delays were most often due to failed parts, methods and tooling, followed by forecast error, and thirdly, due to components or material not available when needed. Almost 50% of the delays fell into the first category. Failed parts methods and tooling is a broad category that was referred to as “production problems” and used to describe component failures within the production process, and operation discrepancies due to either operators or equipment. Given the large portion of delays that fell into this category of production problems, it was beneficial to examine it in further detail. A review of the data available revealed more information on the reasons for delay from failed parts, methods and tools, which is shown in Figure 16.

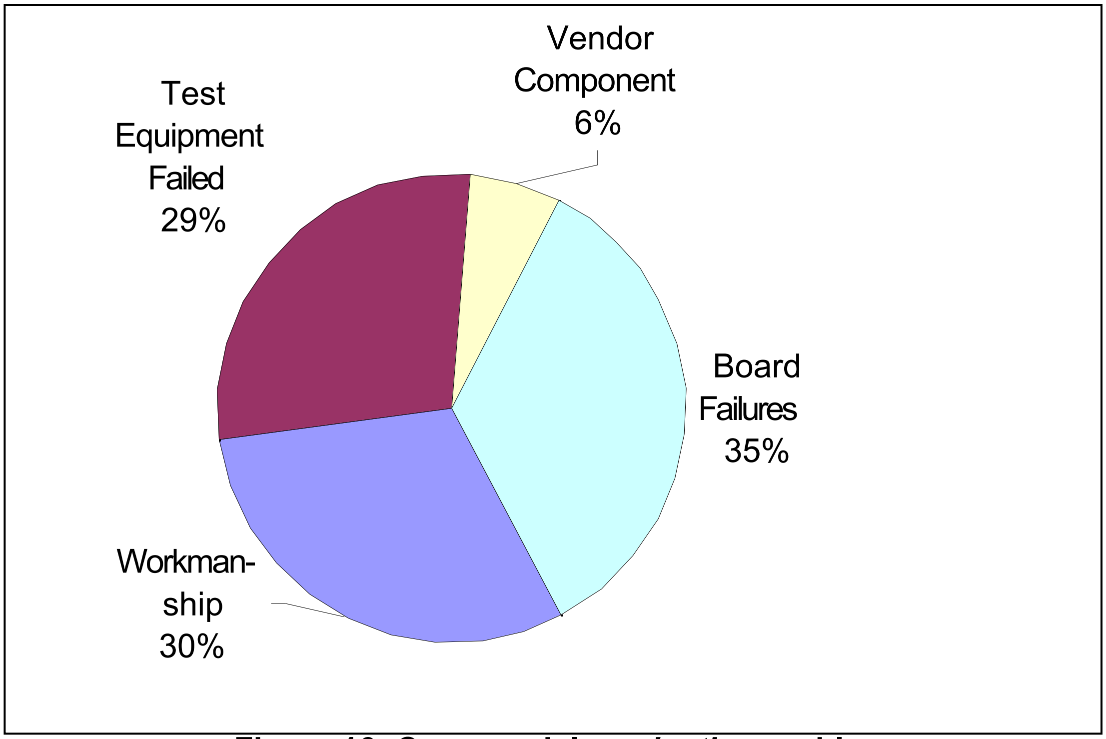


**Figure 16: Commercial *production* problems**

As this chart illustrates, a large portion of production floor problems, 35%, were due to circuit board failures found throughout the process, followed by problems with workmanship, or operator errors, faulty test equipment and finally failed vendor components other than circuit boards. Even further investigation into the data revealed an interesting attribute regarding circuit board failures illustrated in Figure 17.

This data shows that of poor circuit boards that are found in the production process, 74% of them are discovered in final test areas, with only 16% found throughout the assembly inspection areas and only 10% discovered in pre-assembly circuit board testing areas. This indicates a potential deficiency in the screening methods used for circuit boards. Although this problem is attributed only about 20% of the causes for delays, low yields in final testing can have a much farther-reaching negative impact on throughput that will be examined later in this paper.

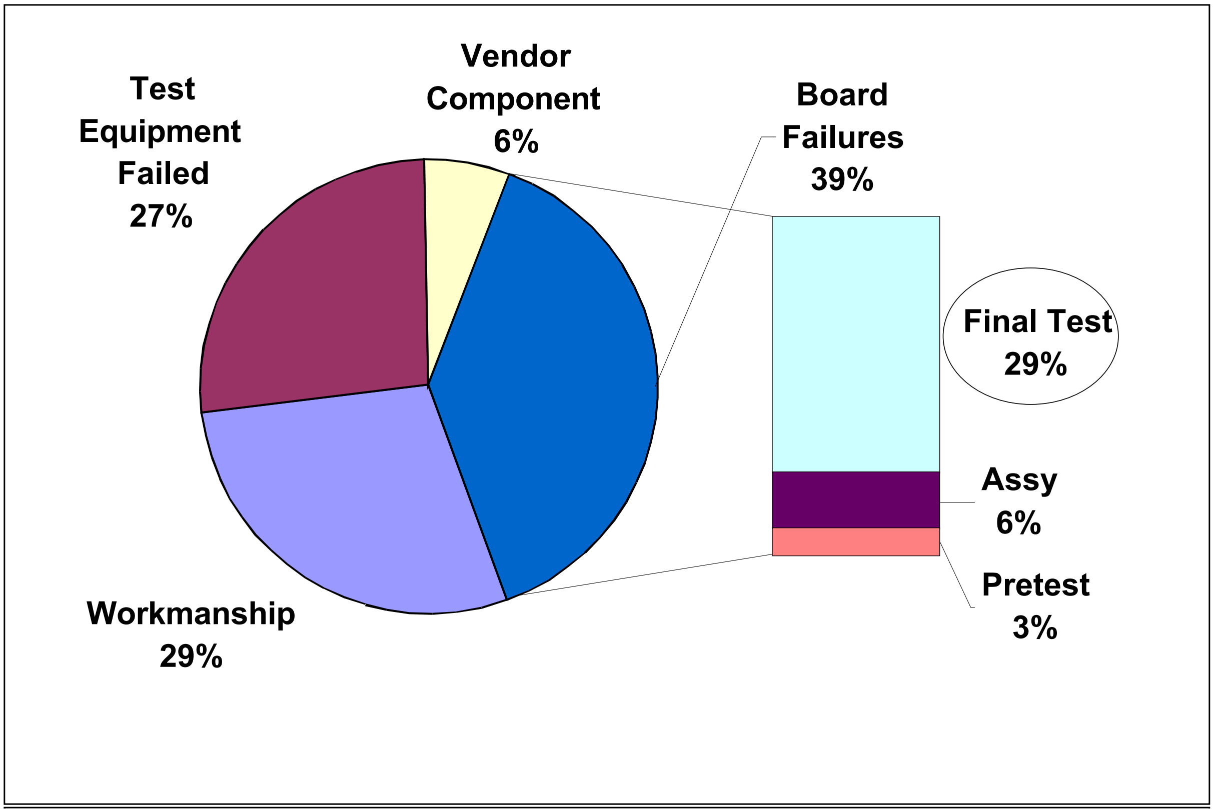


**Figure 17: Commercial production problems discovery**

Workmanship error was another significant production problem. This was mostly due to improper connections made during the assembly process, often times resulting from an improper solder. One of the most difficult operations to control in the entire electronics-manufacturing sector was the consistency and quality of manual soldering. Equipment problems were also common. Specifically, test equipment problems consisting of miscalibration, testing software, or capability issues.

One distinguishing factor in the delays of the commercial sector was that portion attributable to “forecast difference”. Delays, which fell into this category, resulted from perturbations resulting from scheduling shifts of people, material or equipment. Production scheduling and material purchases were often done based on monthly forecasts that were used to generate MRP. Inevitably however, the actual orders placed by customers varied from the published forecast. Although these were commercial products, there was still a high level of interdependency among programs in regards to the sharing of resources, such as personnel and test equipment. Consequently a shift in the required quantities of one system can cause a ripple effect that will disturb the production of other programs.

Other, less significant reasons for delay in this commercial sector were the availability of components for assembly at 8%, and the 2% of delays due to shipping discrepancies. However, there is some overlap in the delay reason of *material shortage* with that of *forecast error*. Since part of the impact of an inaccurate forecast is having an inadequate amount of material on hand, to supply an ordered amount that was significantly larger than that which was planned.

*3.4.2 Defense*

A unique characteristic of the defense business is the contract structure. Drawn-up often for periods of one year or more, the recipients of these contracts have some level of order assurance for that period of time. Order quantities are typically known months in advance of delivery dates. Consequently there is little need to do traditional forecasting. There is no need to try and predict what quantities are going to be demanded, and to construct a schedule and determine material purchasing requirements based on that estimate. This results in a fairly stable schedule of production. An exception is when there are a large number of repair or spare units which make up total demand. In this situation the quantities required would vary more with the change in requested spares. However, as was demonstrated in the engine sector study, even production based on annual contracts can suffer from significant cycle time problems [Ramirez 1998]. Figure 18 shows the top reasons for delay in the defense sites that were visited. These data were also collected from production reports.

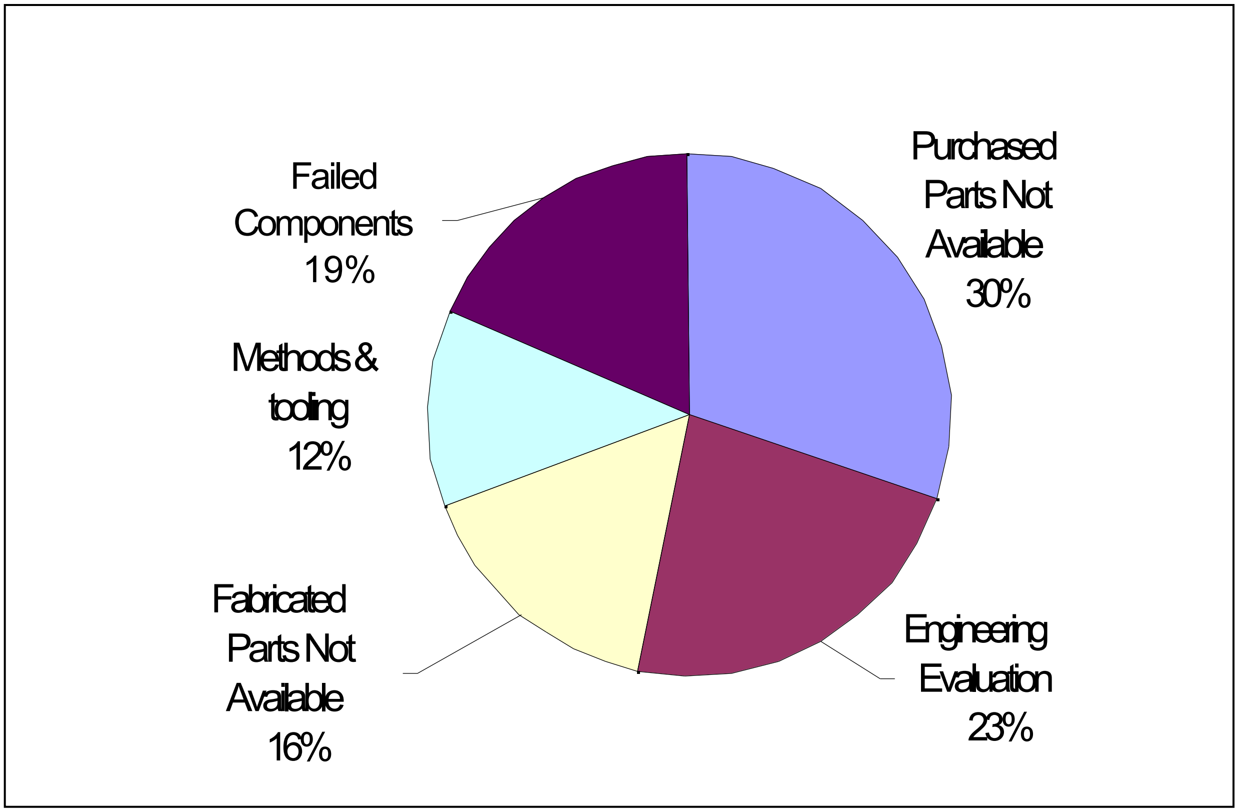


**Figure 18: Defense sector reasons for delay**

There are a few immediate differences from the commercial sector noticeable in this chart. First is the difference in material availability as the largest reason attributed for delays in military. This category was separated into two segments "Fabricated parts not available" and "Purchased parts not available" to help isolate the root causes of these disruptions. Another significant difference was the addition of a category entitled "Engineering Evaluation" and the omission of Forecast difference as a reason for delay.

The unavailability of purchased parts was the primary reason for throughput delays. Further investigation into the causes of material delays showed that the main reasons for this were suppliers having to restock faulty circuit boards which were discovered either in receiving or throughout the process. Secondly, despite the firm schedules given to producers, order quantities were not as stable. These variations at the producer were passed on to suppliers. Consequently, changes in order quantities of supplied components varied from week to week.

The category of “Fabricated Parts” is used to describe the shortage of components that are supplied internally. The supplied components which were most often delayed were circuit boards, and the primary reasons for this occurrence were, capability problems with the fabrication equipment and miscommunication of prioritization on jobs. This last reason stems from the local nature of an internal supplier. Often people from the various internal customer programs that were supplied components, would verbally request that their products be expedited. This practice led to miscommunication on what the true prioritization for jobs was, and as a result created delays by not supplying the right parts at the right time to the right program.

Another major reason for delay reported was “Engineering Evaluation”. This was one of the vaguer categories and has root causes that overlap with other reasons for delays. Engineering evaluation can occur for a number of reasons. The most common of which are evaluation of products which failed a test, evaluation of product which has been reworked, and evaluation of products which are under control for a recent engineering change. Therefore, although engineering evaluation was a category documented by some of the sites visited, it does not serve as a true cause of the delay. To find the root cause we need to look at why the products failed a test, why they were in rework and what causes engineering changes. The first two of these inquiries are the primary reasons for engineering evaluations and lay more in the realm of this study.

To find the answer to these questions we can look at the quality data that was collected. The most common defects discovered in product tests are shown in Figure 19. These were:

- Defective circuit board component
- Bad solder
- Improper component installation

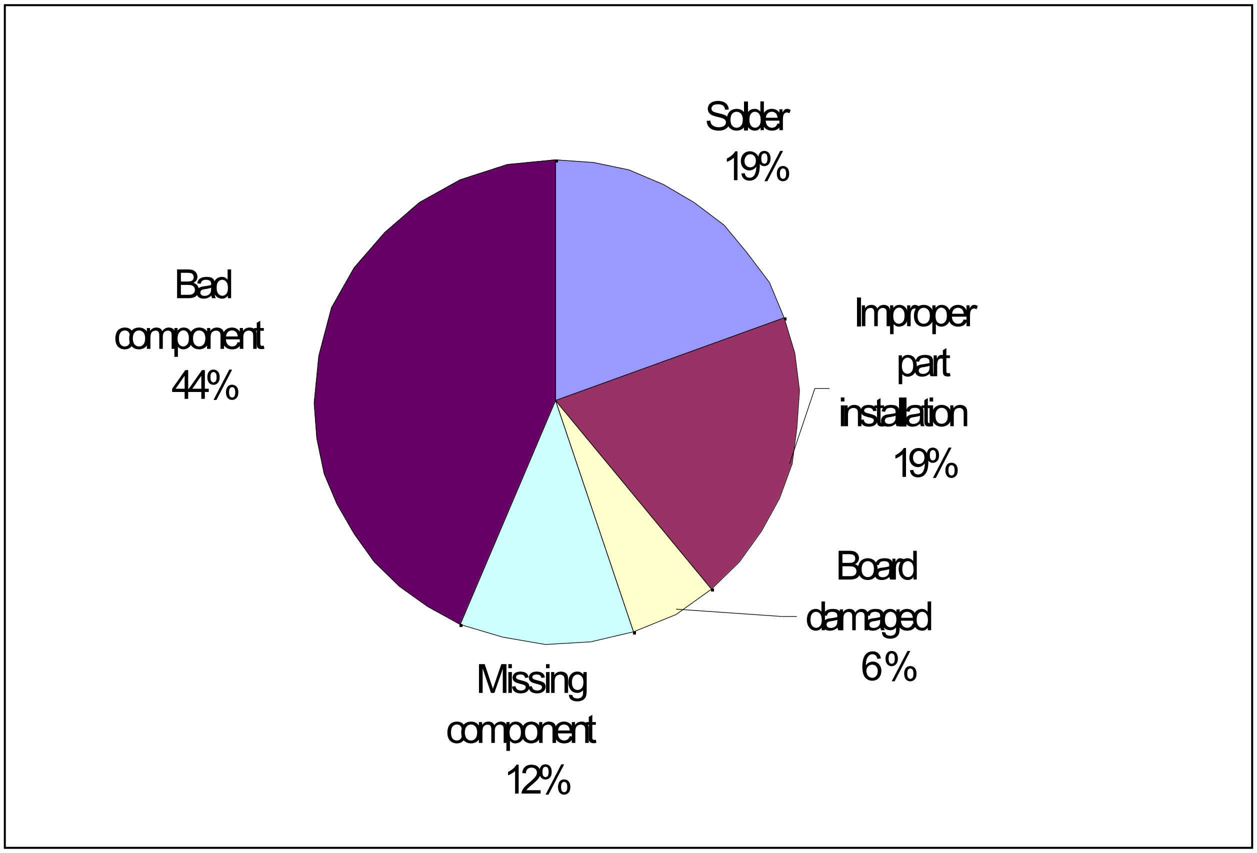


**Figure 19: Top causes of circuit board defects**

The most frequent defect, a bad circuit board component, however, is not solely a supplier quality issue. One of the top reasons for defective components stems from improper handling. A major quality issue at many electronic manufacturers, of any sector, is electro-static discharge (ESD). This problem occurs when people handling sensitive electronic components and assemblies are not properly grounded with personal grounding equipment, which is provided by manufacturers. All sites usually require the use of this grounding technique, but compliance is not usually 100%. Another common source of ESD damage is packing and transportation materials, which should also be examined. One simple and effective way of reducing component defects for program F was by starting an ESD awareness and compliance campaign.

Therefore, problems of engineering evaluation, are often actually problems of component quality and work methods. These are problems that can be improved through sometimes low cost and quickly implemented solutions such as training and the improvement in the availability of proper tools and equipment.

*3.4.3 Management Perceptions*

Thus far in our discussion of electronic sector behavior, we have used entirely "hard" sources of data such as standard reports and internally published plant metrics. To provide a perspective that is different from the data which is gathered on the production floors and information systems of the sites we visited, the persons interviewed for this study were asked simply for their opinion, based on their experience, on what were the major causes of delays in their manufacturing environment. The interviewees included two to three people from each site and consisted of member from the departments of production, engineering, quality or materials. Figure 20 summarizes the results from the responses of the people interviewed.

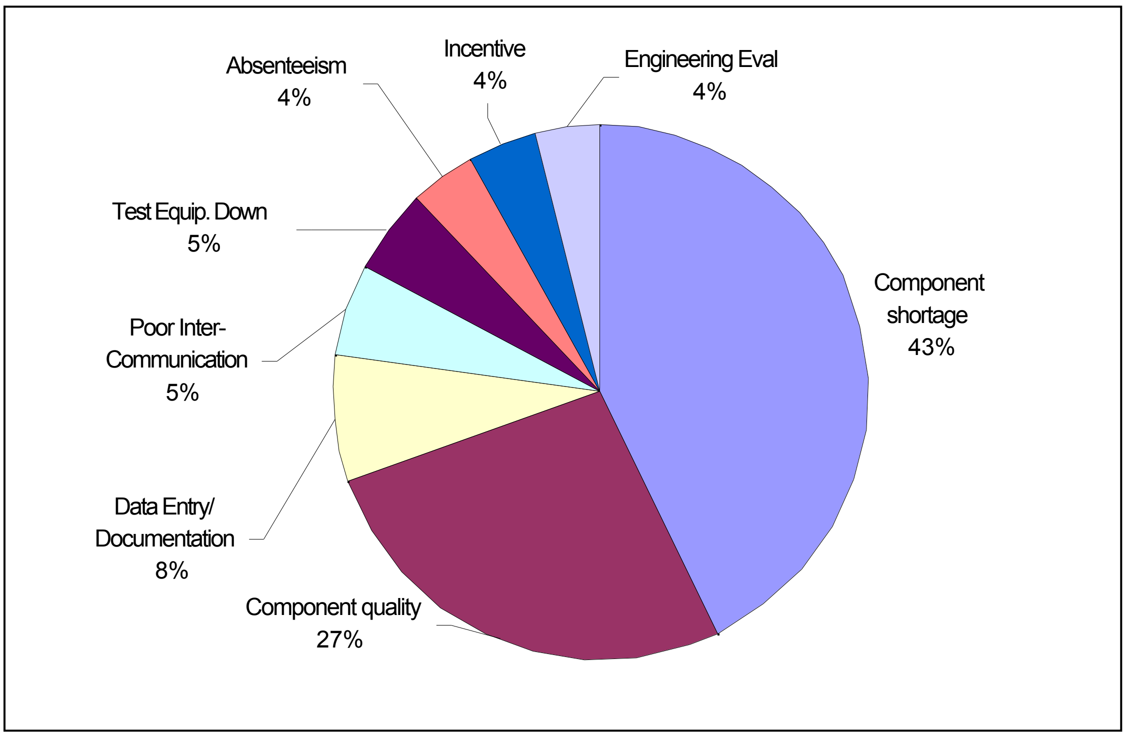


**Figure 20: Perceptions of reasons for delay**

Another issue raised in these interviews was that of inter-departmental communication. This reason for delay was particularly in regards to sites that had internally supplied parts and/or used components that were in common with other programs. The problem was in reference to those situations where an upstream process receives inconsistent information of job priorities from its downstream internal customers, which reside in different departments and silently compete for this resource.  Production people at the upstream process will get mixed verbal prioritization from downstream managers from different departments.  This results in the incorrect ordering of various “hot” jobs with respect to what the true prioritization should be for company’s external customers. Another related problem arises when there is a centralized materials crib and one program will take components that were slotted for another program.  This was referred to as part cannibalization and was known to happen at several of the visited sites.

Other less frequent problems included:

- *Absenteeism,* and the loss of process efficiency resulting from absent skilled operators
- *Incentives*, in reference to the lack of internal structures to motivate production employees to operate in ways that help meet company objectives such as decreased cycle time, defects, and increased employee involvement
- *Engineering evaluation*, this differed from the production reports, which had identified this category as a frequent reason for delay.  It is believed that the reason for this disparity is that interviewees allocated the reasons for delay to the root causes of the need for engineering evaluations, such as defective parts or failures in the testing process.

*3.4.4 Sector Differences*

With the inclusion of commercial programs in this study we expected to identify contrasts as well as similarities in the issues between the two sectors.  Figure 21 highlights some of the main differences in the reasons for delay between the commercial and defense data.

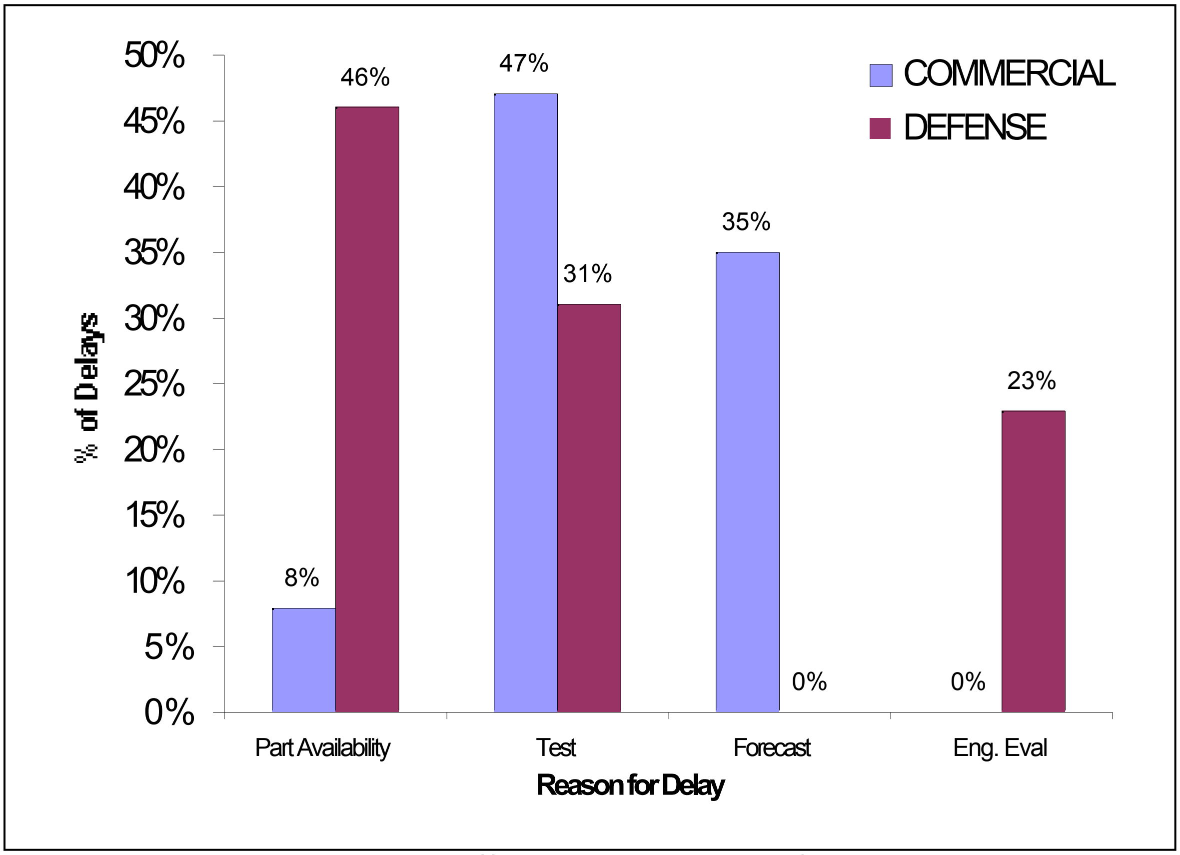


**Figure 21: Main sector differences in reasons for delay**

The most noticeable differences were in parts availability and the categories of Forecast differences and Engineering Evaluation. We touched on reasoning for the latter two earlier. The difference in the availability of parts is likely due to the nature of the products that were examined in each sector. The products on the military side were highly specialized and required custom built subcomponents, whereas the products on the commercial side used mostly off-the-shelf technology. Many of the programs in the commercial side had a high percentage of interchangeable parts with other programs built in the same facility. Consequently, it was easier to have parts on-hand for a specific program in the commercial sector. This, however, also led to a significant amount of component cannibalization, a common problem that compounded the scheduling difficulties encountered with order quantity variations against what was forecasted.

## 4. Implications

We have obtained some understanding as to what are some common elements which effect throughput for the electronics sector.  But the real value of this information comes from discerning its implications on designing and managing a manufacturing environment in this domain.  Let us now look at some of the insights obtained through our discussions with members from the participating sites and analysis of the manufacturing performance data collected in this sector.

### *4.1 Component Delivery*

A top reason for delay involved the unavailability of parts that were needed for the assembly of final units. Material availability was an issue for both external and internal sources of supply.  The components or subassemblies, which were in shortage most often, were those with high complexity or those that used a fabrication process that was unique to the pertinent application.  Many companies also struggle with the question of whether to manufacture these components internally, or to outsource.  Apart from being a strategic concern when utilizing unique electronic architecture, it is believed that by having components and subassemblies produced internally there will be greater control in the management of these supplier groups and their delivery.  But this has not been evidenced in our study.  Actually, the contrary to this logic has been observed.  One will recall that a significant reason for delay was miscommunication with in-house departments that supply components to various programs.  Because of the fact that they are in-house, they are subject to more frequent changes in order prioritization, when there are informal scheduling policies in place.  These internal suppliers would benefit from having a formal scheduling policy that clarifies what the overall priority of jobs is, on a real-time basis.

One of the most troubling compromises to those who wish to create leaner systems is that of balancing low inventory with part shortages.  A lean system strives to carry as little inventory as possible.  But since decreasing inventory also decreases the safety buffer of products that are on hand, there is incentive to have more inventory as a protective layer against unforeseen perturbations. This highlights the importance of focusing on creating a system first, that can support a low level of inventory, a supply system with low defects, with low variability, high reliability, and which is highly responsive.

Procurement of key production components also needs to be closely managed to improve timely delivery of materials. Suppliers, whether internal or external, need to be held accountable for meeting delivery. Material managers would often be asked why their suppliers are late with components, and virtually no one had a confident answer to this question. In the next section of this paper, we will discuss how some sites have improved the timely delivery from both internal and external suppliers through simple scheduling rules and procurement organizational design.

### *4.2 Minimize Disruption of Engineering Changes*

A common cause of engineering evaluation and the delay of components necessary for production was engineering changes. There are a number of possible efforts that can alleviate the negative effect of engineering changes on the flow of production.

- *Communicate impact to customer*: often times changes are requested by many program customers. However, these changes are often done without knowledge of the impact on delivery, quality and the cost implications. Consequently, it is important to have information of the level of disruption, which a change request can cause. Experience suggests that customers can often make changes with uninformed regard on the disruptions that these requests cause throughout the supply chain. There is a threshold that limits the benefit a change can bring to a program based on factors such as program maturity with respect to product lifecycle, and costs of implementation. This concept of a change "hurdle" should be understood and shared with program engineers as well as customers.

- *Early product involvement in product development*: It has been demonstrated (Hsu, 1999) that the number of engineering changes in a program tend to be reduced, the more involvement a supplier has in the customers' product development process. In particular the participation of manufacturing engineering staff can reduce the problems found throughout the production lifecycle that will require a product design change.

- *Design for Manfacturability*: Increasing consideration during the design phase for the assembly of a product also helps reduce the need for design changes once the program is in production. Simplicity in design, standardization, and minimizing the number of total parts used, can decrease the frequency of engineering changes throughout the lifecycle of a product. Data from our study supported the link between the complexity of a product and the rate of engineering changes in that program which is illustrated in Figure 22.

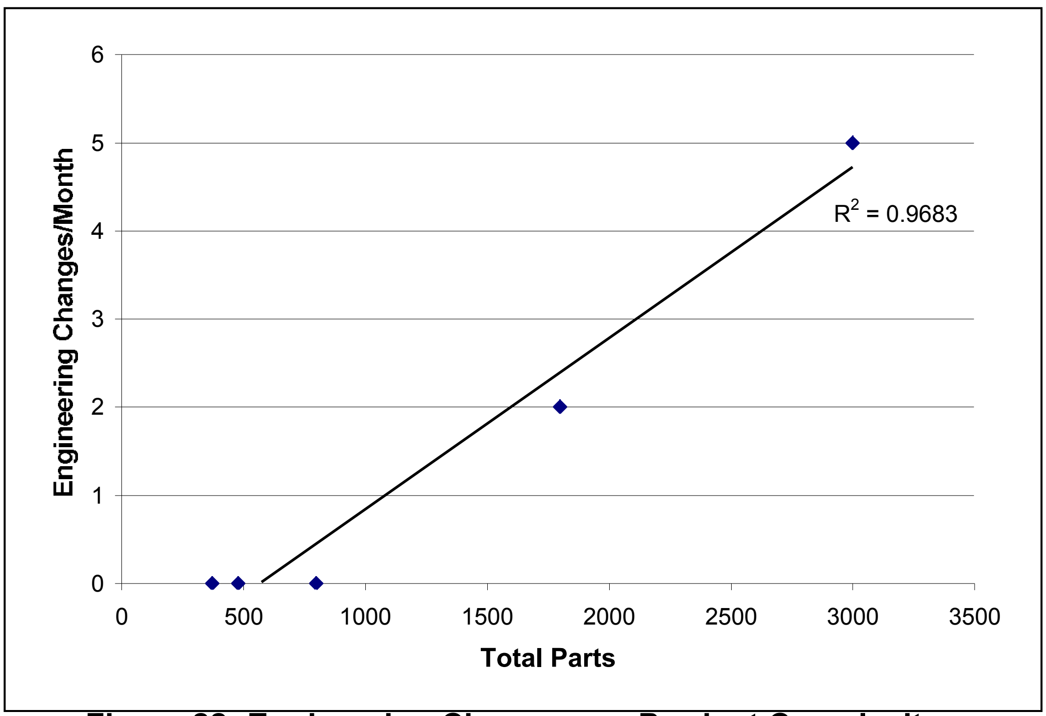


**Figure 22: Engineering Changes vs. Product Complexity**

- *Change implementation windows:* One method of reducing the disruptiveness of engineering changes is by pooling them and implementing them at designated windows of time, for example once every three or four weeks, in particular class 2 changes, which do not involve design but can delay material for documentation revision purposes.

Although it is difficult to control the need for a design change, particularly since it is closely related to the maturity of a program and customer design requirements, these measures can help mitigate against the frequency and disturbance of these changes on the throughput of a process.

### *4.3 Yield effect*

Testing was cited as a major constraint to throughput at 4 out of the 5 sites studied. This concern was mostly manifested in the delay categories of failed parts, methods, tools and, engineering evaluation, as well as in numerous complaints by production management regarding the inability to get parts through testing with sufficient efficiency.

#### *4.3.1 Production and Testing Simulation*

To demonstrate the influence of testing on delays, a simple model was designed of a typical production flow in electronics manufacturing. The model, stripped of some modeling structure for clarity, is shown in Figure 23. It represents the movement of material through an assembly and testing phase and models the effect of yield rates on throughput and delay. A fraction of the units are successful in testing and are passed on to be shipped. The units that do not pass the test operation are sent through an engineering evaluation and then a repair phase and then sent through the tester again. If there is a large build up of backlog then more resources are allocated to the tester, and reworking areas, increasing the capacity in these areas, similar to the use of overtime in a manufacturing environment.

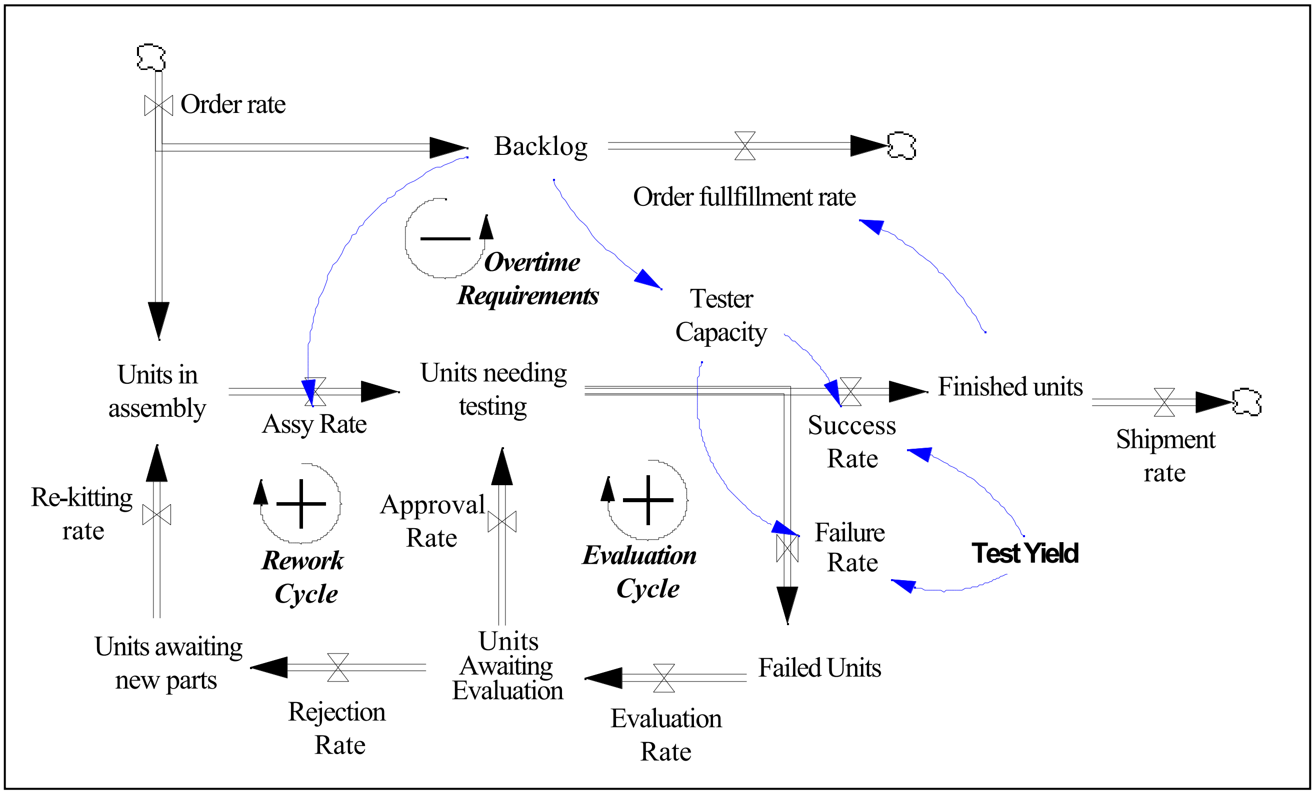


**Figure 23: Basic production system model**

The significant dynamics in this system occur through the detrimental evaluation and rework cycles which have negative reinforcing effects on the backlog, given a limited number of resources in the production and testing areas. The reason is that for every product that does not get through testing there is an increased burden placed on the assembly and testing areas which have to work on the same product more than once, while still having to handle the incoming orders. What this model demonstrates is that a point of high leverage in this system lies in the yield rate of the testing process, because it effects the "valve" which feeds the reinforcing loops in the system. The simulated result is shown in Figure 24, and illustrates the non-linear effect of test yields on delays. In other words, with an incremental improvement in test yields the system gives a larger positive effect in throughput performance (reduction in delay). This plays true regardless of what numerous other external factors are present in the real-world system that this model represents.  As long as one agrees that the basic structure represented in this model exists, then so too does the yield effect.

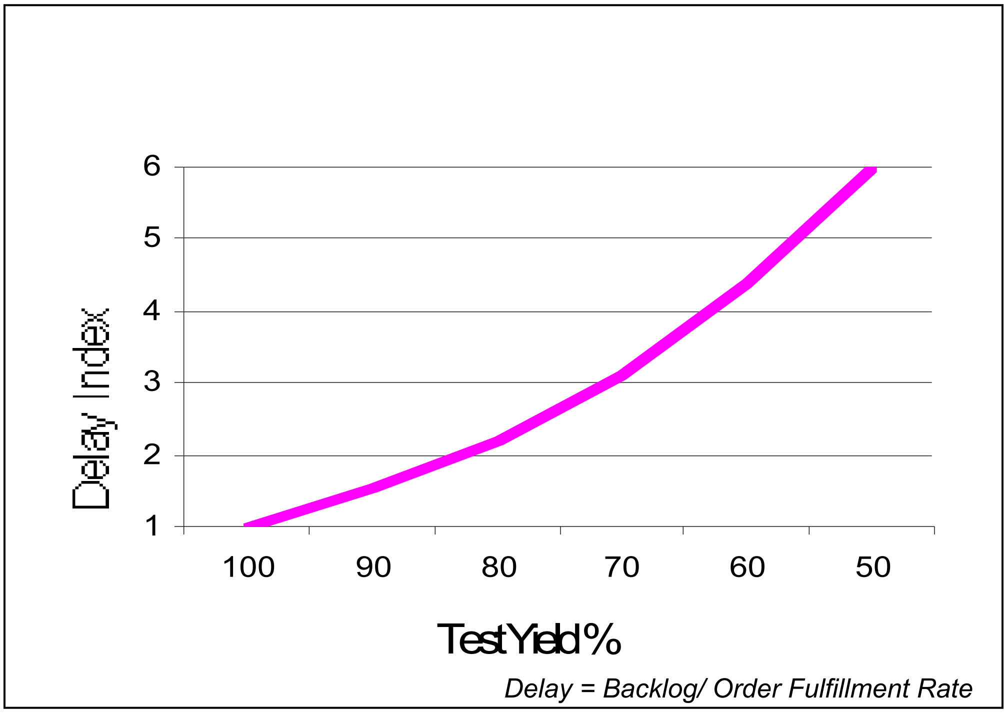


**Figure 24: Test yield effect on delay**

*4.3.2 Field Supporting Data*

The effect of test yields on throughput performance was observed in various programs during this study.  Figures 25 and 26 show the effect of increased test yields on throughput over a yearlong improvement effort at program F.

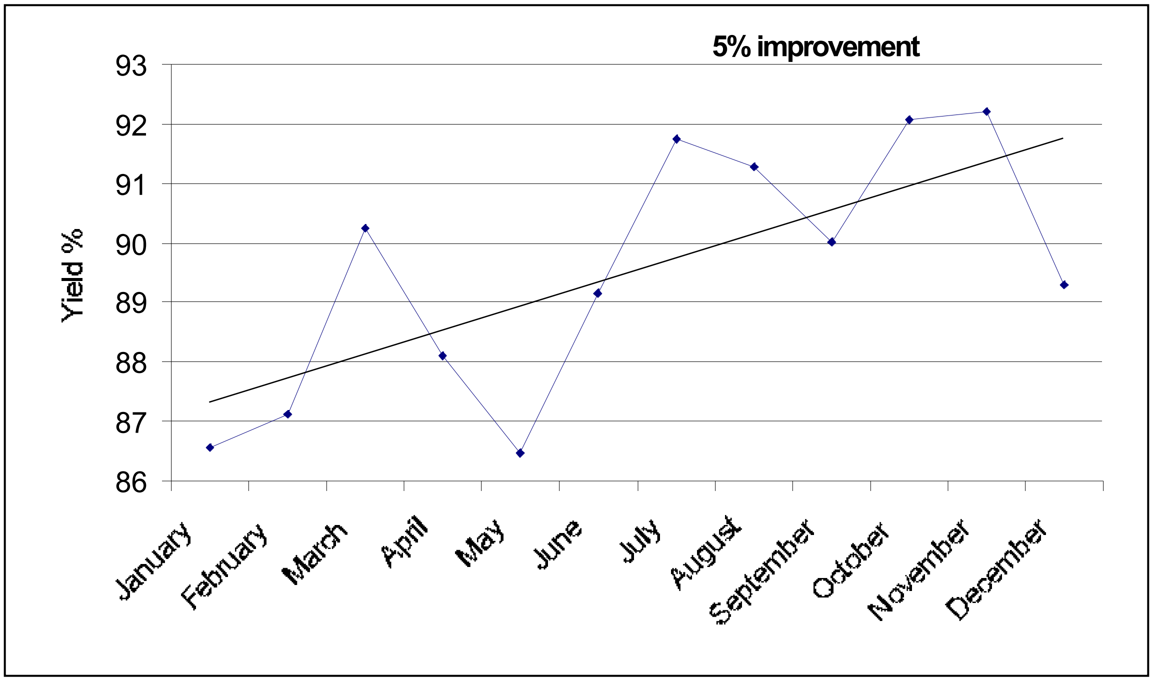


**Figure 25: One year test yields at Program F**

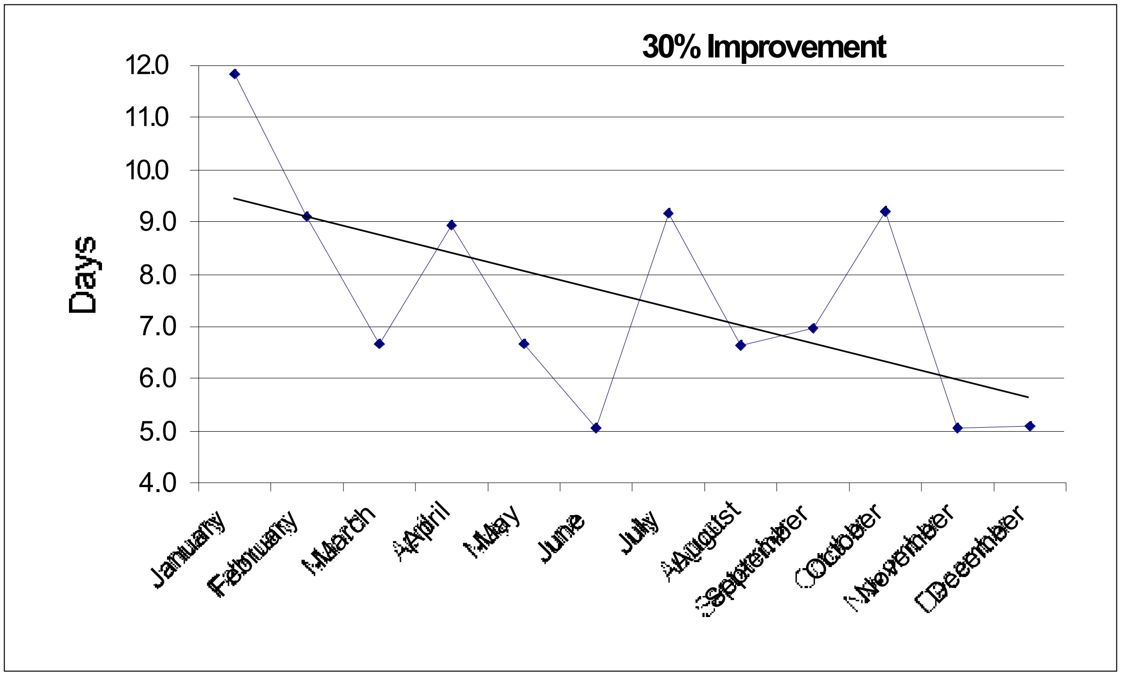


**Figure 26: One year average cycle time for program F**

Analysis of data in the other programs showed a correlation between yield rates and throughput performance (defined as actual build time/planned build time). This relationship at program E is illustrated in Figure 27 which shows the cycle time performance (actual/planned build time) plotted against defects per million opportunities, also known as DPMO's or PPM Defects.

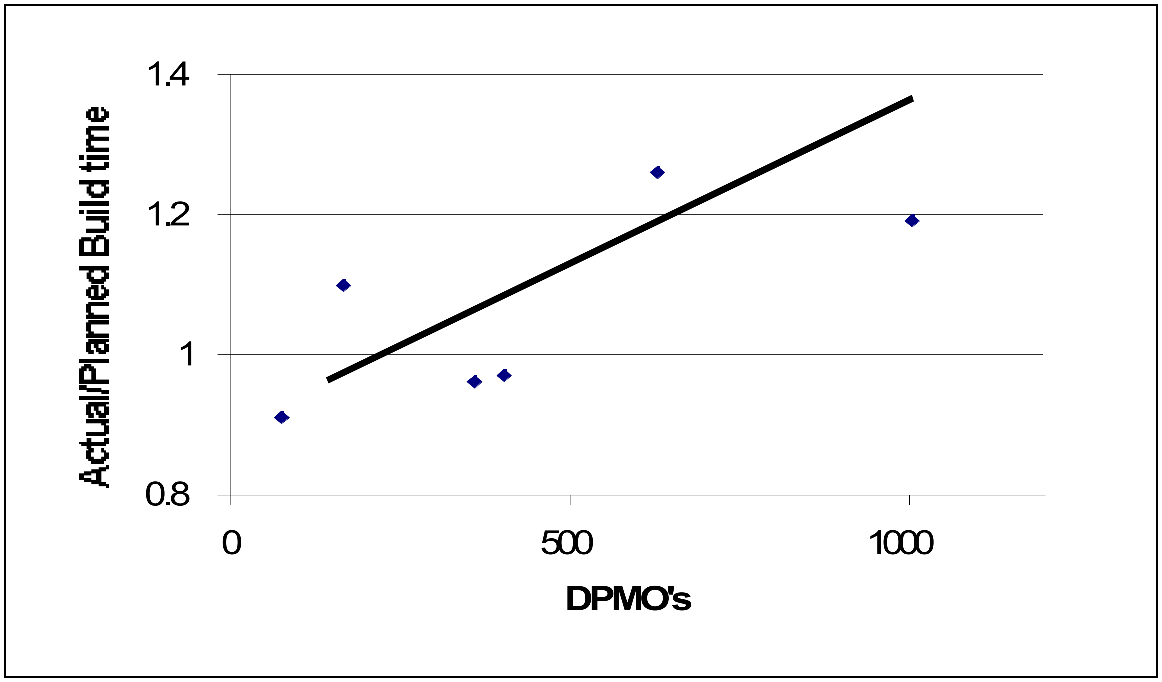


**Figure 27: Cycle time performance vs. DPMO for program E**

Data from our research also showed an 80% correlation between throughput yields (the probability that a product passes through a system without a defect) and on-time delivery for this sector. This relationship is shown in Figure 28.

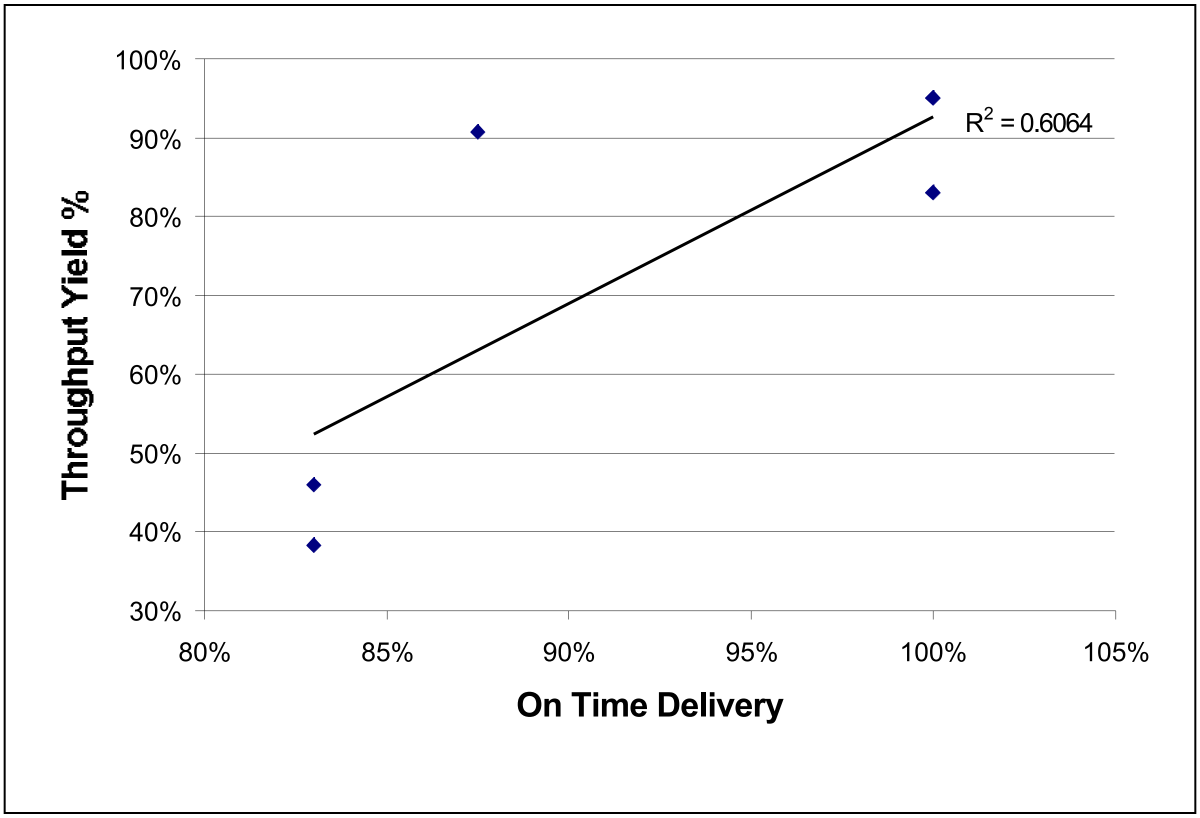


**Figure 28: Throughput yield vs. On time delivery**

There is, of course, an important trade-off issue. With the high level of complexity in some products it can become extremely difficult and costly to obtain a 1% increase in yields. It is due to the simple principle of interrelated reliabilities on a system. When you have multiple circuit boards in a final assembly even a 99.0% reliability in each board will only yield 95% yields on a system with 5 boards. However, with continued improvements in electronics manufacturing technologies, component reliabilities in excess of 99.0% are not uncommon.

*4.3.3 Test Yield Determinants*

Given the significant dependence of throughput on product test yields, it would be helpful to understand what the factors are which heavily influence these yields. Based on interviews with those who worked closely with test equipment at the different sites visited, the following list of variables was compiled.

- *Board Quality:* One obvious influence is the quality of incoming circuit boards. A significant portion of the defects captured in final testing result from deficient board quality. Data collected from the programs showed a 70% correlation between the level of defects captured in the assembly process and the yields produced at the final test. Figure 29 shows this relationship for one of the programs.

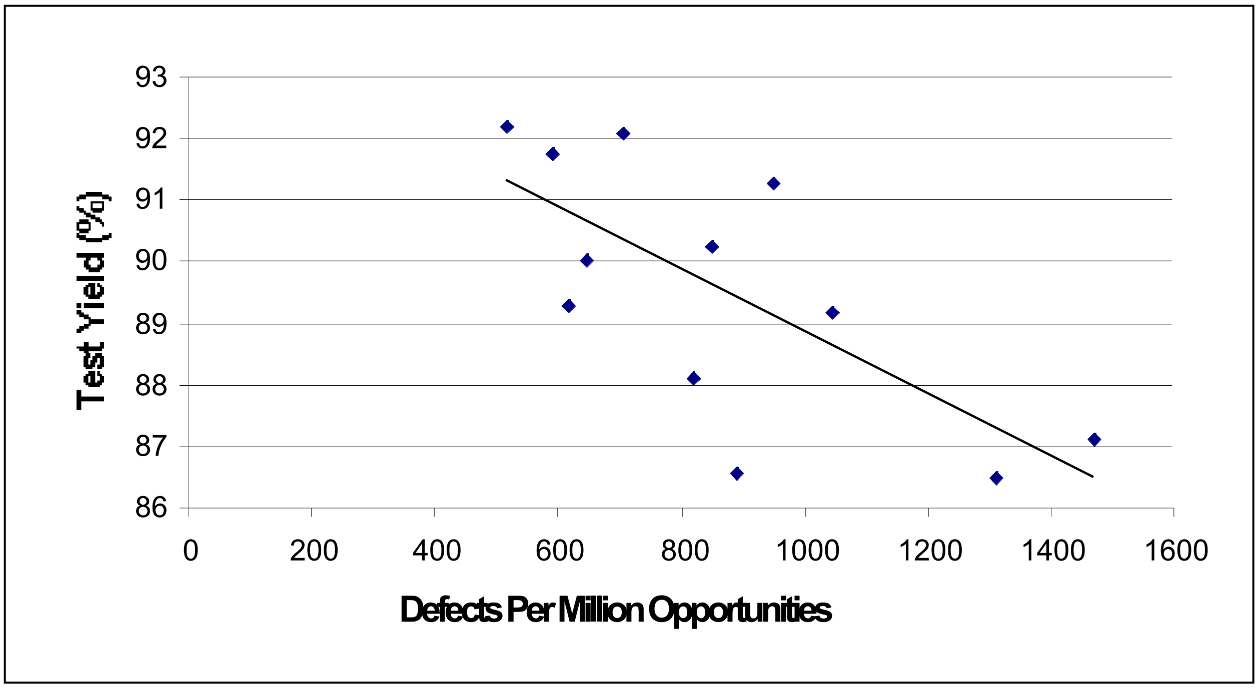


**Figure 29: Test yields vs. Process defects**

- *Upstream Testing:* An implicit rule in electronics manufacturing should be, test early and often. The ability to catch defective components early will eliminate defective products at the final test stage. The effect of having defects travel throughout the production process only to be captured in the final test area and sent to rework has been demonstrated to have a negative reinforcing effect on the flow of materials throughout the production process. Although most facilities incorporated some kind of visual inspection in their assembly processes, only one site had actual test fixtures at each work station that tested at least for electrical continuity in the subsystems that were created.

- *Robust Assembly Process:* Apart from poor quality with the incoming subassemblies to a production area, defects caught in the final test phase are often created in the process of assembling and transporting material. The proper handling of sensitive components can have a significant effect on test yields by reducing broken and damaged components as a result of transportation or ESD.

- *Equipment Reliability:* The capability as well as reliability of the test equipment is another important factor. This would also include the concept of test repeatability and reproducibility. Many of the more complex testing facilities, such as those used for extreme environmental testing, require specially trained operators. Test equipment should have effective preventive maintenance and calibration programs, to avoid unexpected breakdown. Four of the sites visited had data on test equipment uptime, and they showed a significant relationship with throughput yield. This data is illustrated in Figure 30.

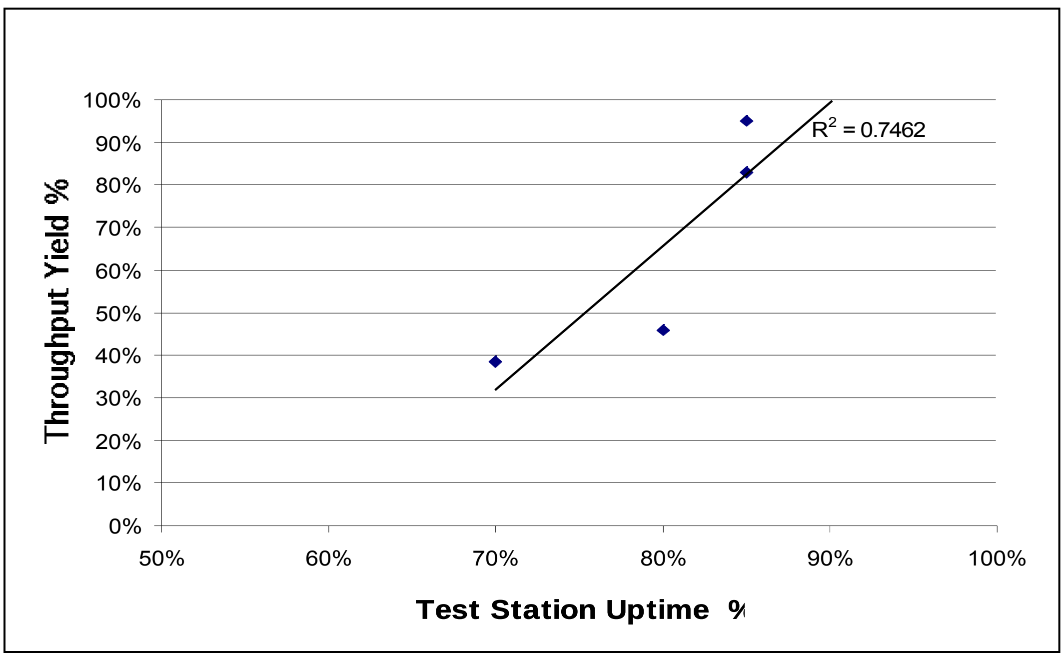


**Figure 30: Throughput yields vs. Test station uptime**

### *4.4 Optimize Test Equipment Usage*

Data from both commercial and defense sectors demonstrated that most of the product failures were not being caught until the end of the production process. This however, is the worst stage at which to realize that there is a defective component installed in a final assembly. The reason is that the further downstream a defect reaches, the more work and cost which has been incurred on that product, and the further work and cost will typically be created in repairing the product. In addition, final test equipment is often the bottleneck operation in EC manufacturing, and to catch a defect at this stage is to waste valuable use of this resource, which has a direct impact on the production system's throughput.

It is important to note that final testing was the bottleneck for most of the sites visited, consequently this operation needs to be monitored closely and managed to minimize the waste incurred at this critical step. Ways utilization of this operation can be improved include:

- *Efficient test fixtures*: Products use specially designed fixtures to connect to the test equipment. These fixtures should make it as quick and simple as possible to set-up a unit, minimize the time to run a cycle and/or maximizing the number of units which be run on one test cycle (for multiple unit testers)
- *Minimize test equipment downtime*: To maintain a consistent flow through this operation, unexpected downtime should be minimized through preventive maintenance and a responsive support team. Problems in testing are almost inevitable but the root causes should be sought and corrected as was done in the case of program F. In addition the time to fix an issue at a test station should be minimized.
- *Upstream testing*: To minimize the failures that occur at the final test stage, it is imperative that defects are caught as far upstream as possible. Ideally defective components are eliminated and caught at the supplier, but efforts should also be taken to detect and eliminate defects throughout the assembly process with the investment in simple checks such as continuity and basic functionality tests at different stages of production.

### *4.5 Circuit Board Quality Is King*

If there is one aspect that will be overemphasized in this paper, it is that of circuit board quality being critical to the effective and efficient operations of an electronic component manufacturer. This theme underlies almost every issue and concern that has been brought up in our site visits, and which has been discussed in this paper. If the top three disturbances to throughput and cycle time were revisited, one will notice that the root cause of these disturbances is circuit board quality.

- *Component shortages*: Root causes for this issue included, the unavailability of parts that are needed for the replacement of defective ones, and the cannibalization of components due to failures in an originally designated batch.

- *Failed Final Assemblies*: As was demonstrated earlier, the primary reason for test failures is defective components This can have a very negative effect on the entire production system when resources are expended to rework and evaluate failed units. When circuit board quality is improved, test yields also tend to show improvement.

- *Engineering Evaluation*: This circumstance typically occurs when either an assembly fails a test, a product has been reworked and needs to be checked, or there is a design change which requires engineering to approve products during the implementation of the change. The influence of board quality to the first two of these reasons is clear.

Consequently, every effort needs to be made to assure the quality of these subassemblies. Whether these boards are produced internally or externally, high quality levels and continuous improvement need to be the primary criterion for the sourcing of this business. Some immediate improvements can be achieved without major investment through worker training, analysis of packaging materials, and ESD protective equipment. In the next section of this paper we will look at how some organizations are addressing this issue through the formation of specialized production areas for these critical components.

## 5. Manufacturing System Design Attributes and Best Practices

A system can only perform within the limits of its design. Therefore it is important that part of the purpose of our research is to provide information into how manufacturers are designing and managing their production systems to mitigate the effects of variability both inside and outside the production areas so as to minimize disruptions in throughput and improve overall performance. Although it is not possible to document every one of the valuable practices which was observed throughout our research, we believed it would be helpful to highlight some of those practices which seem to be effective in guarding against many of the issues, concerns and causes for perturbations in the systems we have studied. The approach we will use consists of examining major components of the supply chain, and discussing some of the system designs we have observed that performed especially well in those areas.

### *5.1 Materials and Procurement*

We have discussed the issues associated with the timely delivery of materials from sources inside and outside the host organization. There are a number of efforts however that are being proven effective in lessening the frequency of this problem, which we will now cover.

- *Commodity Manager vs. Program Materials Manager*: One site where the delivery of external materials did not seem to be a major issue was at Program C. One reason was the design of the materials organization. Whereas some companies organized their materials management department by commodity, Program C had it structured by program. A commodity manager is responsible for a category of materials or parts across many programs in the company. This structures is often used to maximize discounts received on large quantity purchases. A program materials manager however is responsible for a set of materials for one program. The advantage of having a program materials manager is that accountability for the program is better defined.  For example, in program C, the materials manager would have a list of all the components on order for the program and he would communicate continuously with the suppliers on the status of these goods.  By keeping “a close eye” on supplier commitments as compared to the program C requirements for a period, he said he was able to catch problems far in advance and resolve them as necessary to prevent a shortage in the factory.  The resolution could be from a new rationing of parts available or looking towards an alternate source of components.  The assignment of one person to one program simplifies coordination at the producer and limits potential disruptions in the entire factory.  Whereas in the commodity management structure, a break in a link of the procurement organization can result in delays across all the programs in a company.  In addition, a chief program manager who wants to monitor the schedule of deliveries for her or his program would need to contact numerous persons (in the commodity structure), as opposed to the one or few people responsible, in the program materials manager structure.  Sometimes a hybrid structure works best where a program manager is used for 80% of materials which are unique in design or high in value for a program and the remaining parts are handled by a commodity manager to gain economies of scale on the materials which are most in common across various programs. Figure 31 illustrates the different organizational structures for materials management.

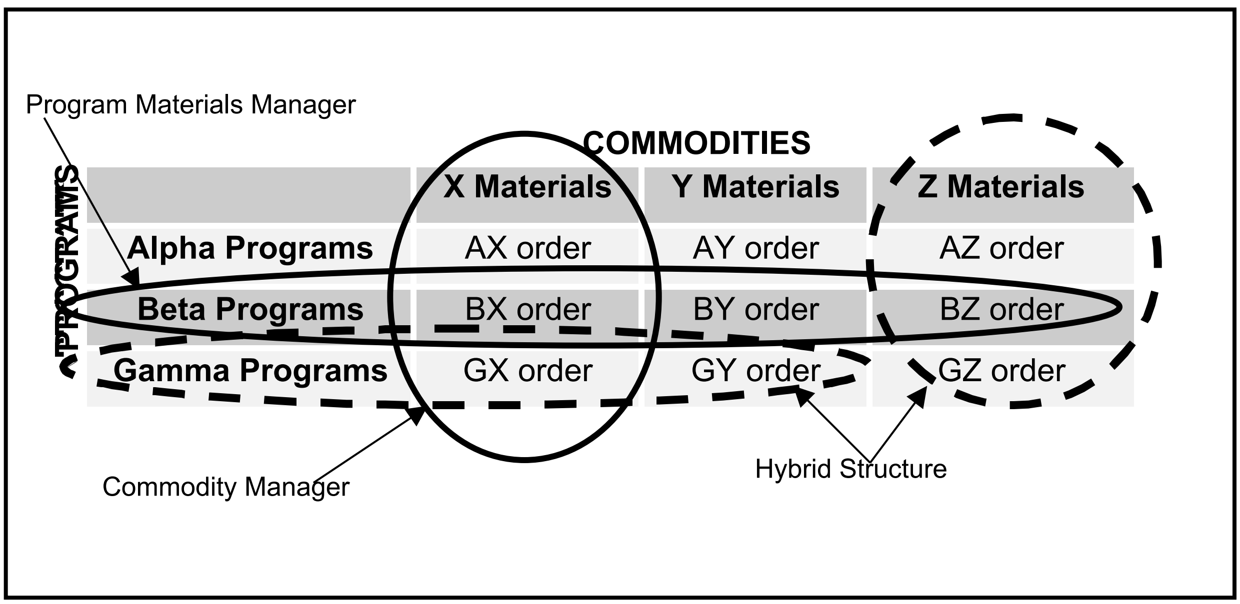


**Figure 31: Materials Management Matrix**

- *Automated stock system*: To better track and deliver the components necessary for each day's production, program B invested in a semi-automated material storage and retrieval system. Every component inventoried and consumed was accounted for using a barcode system, and kept in a designated section within a designated bin. The system had an automated stock storage and picking system which kept track of what quantities of: each component were available, which department consumed components, and where in the approximately 50,000 available storage units it was located.
- *Certified Suppliers:* In the automotive industry, supplier certification is virtually required for consideration of business. Having to expend time and effort assuring that the product you are purchasing is of acceptable quality should be an unacceptable waste. This is a practice that needs to be instituted with more frequency at electronic component manufacturers for the defense sector. Both of the commercial manufacturers in this study had a supply base that was 100% certified but defense had an average certification level of 43% with a wide range of 0 - 9 5%. Figure 32 shows the distribution of this practice across the sites visited.
-

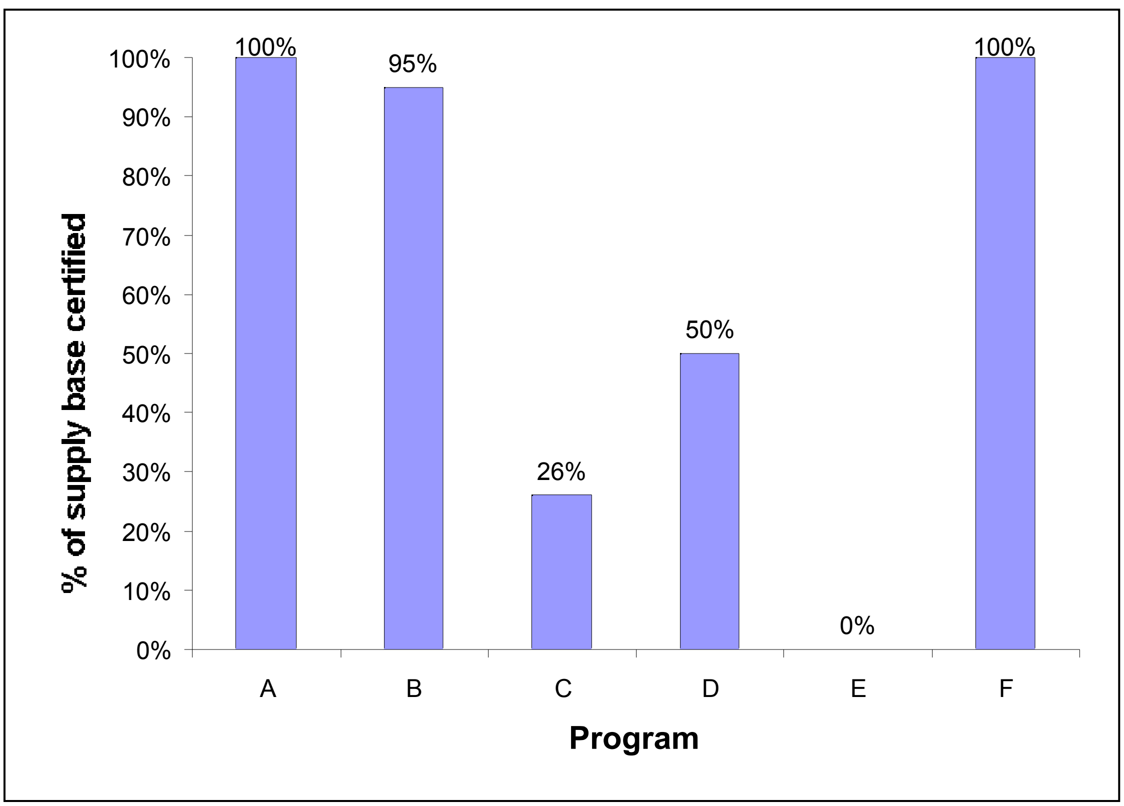


**Figure 32: % of supply base certified, by program**

Certification of suppliers not only increases the accountability for quality but also decreases the cost of ownership of purchased parts, reduces the need for incoming inspection resources, and reduces the total cycle time.  In addition there was a correlation found between the % of certified suppliers and the % of supplied components delayed in production which is shown in Figure 33.

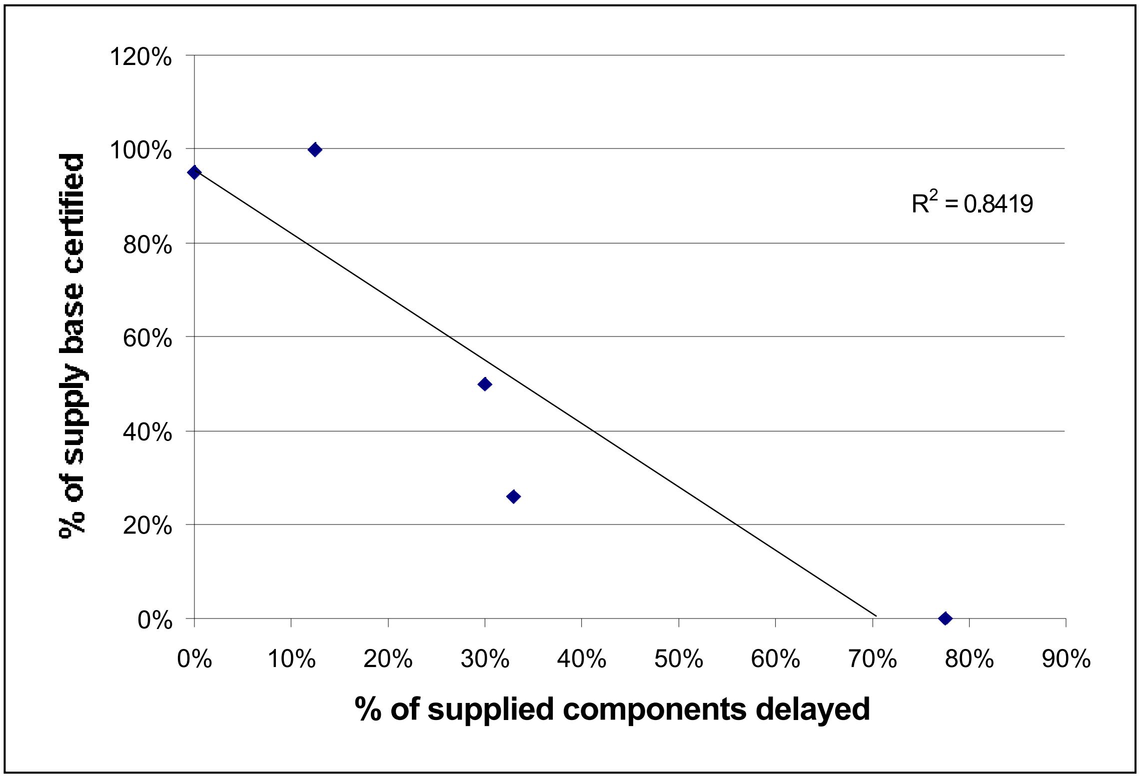


**Figure 33: Supply base certification vs. Supplied components delayed**

- At the site of program D material delivery occurred in a uniquely lean manner. There was no central warehouse for these materials rather, as was mentioned earlier, supplies were delivered directly to production area for this program.  If the material came from a certified supplier it would be sent directly from receiving to the production area without passing through the incoming inspection that all other components had to pass through.  By switching towards these satellite stations this site was able to free up over 25,000 square feet (across various programs).  In addition, this practice reduces costs of packaging, transportation, and the cycle time incurred in getting material from dock-to-stock. This is a prime example of striving to have *the right thing, at the right place, at the right time*.

### *5.2 Circuit Board Fabrication*

We have discussed in some length the importance of circuit board integrity and of taking proactive efforts to improve it. There were two practices observed which are acting on this and have shown considerable results.

- *Defect prevention teams:* In an effort to aggressively combat the problem of defective circuit boards, program F, instituted what were known as defect prevention teams. These were cross-functional task forces created for the sole purpose of using disciplined problem analysis and solving methods to reduce defect levels. Figure 34 illustrates the results of this initiative over a 12-month period, showing a clear decline in average defects per million opportunities in that time, as well as, decreased variance in this measure, indicating an improved control of the production process.

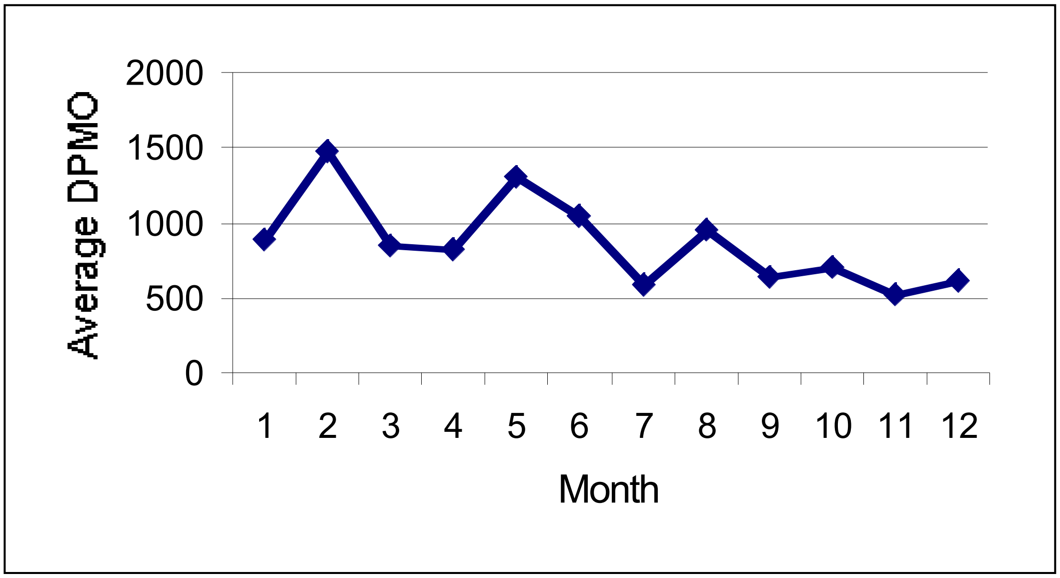


**Figure 34: Results of defect prevention team at program F over 1 year**

- *Specialization Centers*: Two sites in this study had established manufacturing centers which specialized in making circuit boards. These companies considered circuit boards a core technology which could be produced best in a centralized location where specialized research and development, engineering, and manufacturing personnel could focus all their efforts on making boards of the highest consistent quality. Program E had, prior to the time of the visit, shifted the sourcing of their boards from an in-house production area to such a specialty center. The results of this change were reflected in their measure of PPM (parts per million) defects, which are shown in Figure 35.

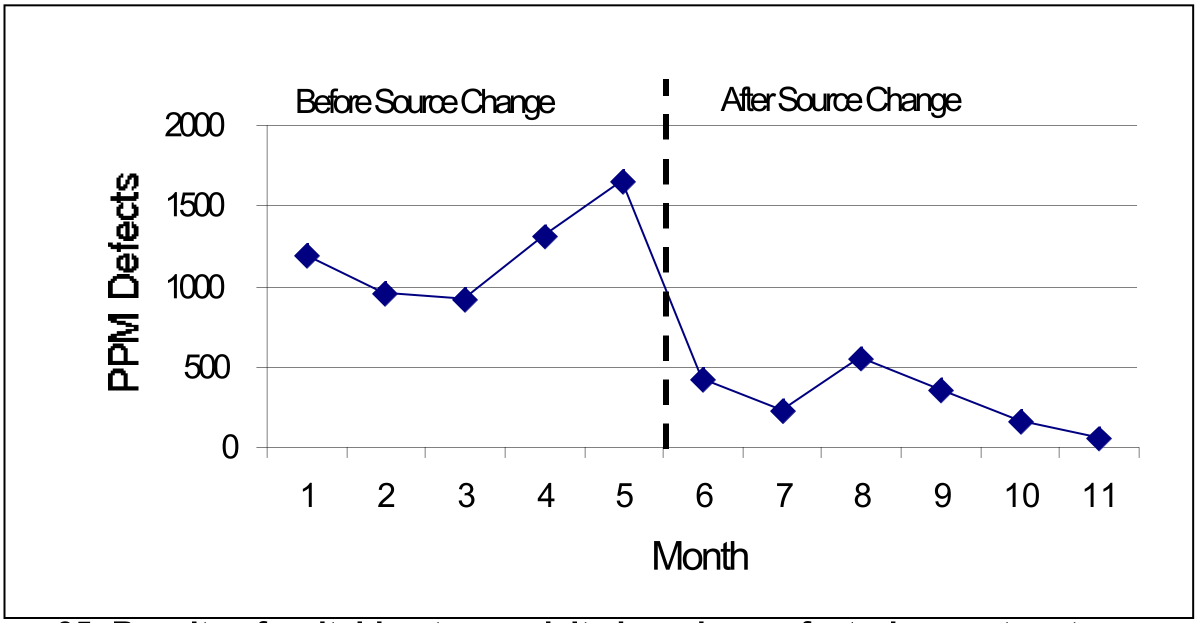


**Figure 35: Results of switching to specialty board manufacturing center at program E**

Although this point was brought up recently, it is worth restating that another way to improve the quality of the circuit boards arriving into an assembly process is to require that they be sourced from certified suppliers who demonstrate the practice of continuous improvement in their operations.

### *5.3 Production Management*

The general assembly area of EC manufacturing, in one sense, is an example of traditional manufacturing. Not unlike the craft manufacturers of Swiss watches in the early 1900's and prior, assembly technicians sit at a well equipped table, often times with a well lit magnified lens between them and their work piece and a soldering tool at their side for the fastening of components and repairs. But even in this typical setting, there were some less than typical nuances of manufacturing strategy that are worth noting.

- *Programs C & D kanban systems*: Examination of cycle time performance across all of the defense sites in this study shows that programs C and D, which were produced at the same site, had significantly better performance and lower variation than their counterparts in this sector. The superior performance in these aspects we believe can be attributed to the tight coupling of operations that was established through their internal Kanban system design. There were some interesting contrasts with program B that were also observed. Program B had the most comprehensive MRP system of all the sites visited, with continuous, detailed information on every operation and person that came in contact with a product. Yet it may not have been as effective in creating as smooth and lean a flow and in actually controlling its processes as the kanban system was. Programs B, C, and D all consistently achieved 100% on-time delivery to the final customer. But what is particularly interesting is that Programs C and D did so with significantly less variation, better internal MRP performance, and with a production system that was controlled by the use of bins and kanban cards rather than the use of an extensive and highly integrated MRP system. In addition, the control of WIP required by the kanban system allowed them to carry about half of the total inventory that other defense sites carried. Now this kanban system is certainly not the panacea of manufacturing strategy. It is very difficult to implement this type of design without the support of a stable production process and a patient staff that is quick to respond to the problems that working within this type of system can often cause.

- *Workstations vs. Assembly line*: It is not likely that every site used a workstation arrangement out of shear coincidence. The question of " when is it best to have a cell-type system and when is best to have an assembly line- type system" has no clear answer. But it was interesting to learn from the transition made at program D that the cell, or workstation-type system gave a perceived improved performance in a defense program that operates at volumes that are higher than those which are common for military contracts. Perhaps it is here that we obtain some additional value in examining program D, this stray point of product volume and complexity in our study. There is value in understanding that the benefits of production using workstations, where a broad level of operations are performed, are independent of volume; benefits such as an increased sense of ownership on the part of the operators, increased acquisition of skills, a greater variety of tasks, increased requirement for operator insight, and agility in operations.

- *Roller-stations*: While on the topic of workstations, a beneficial practice that was observed in general assembly was that of having all workstations and other equipment affixed with wheels for easy movement. This practice is in line with the concepts of agile manufacturing and continuous improvement. This was practiced at program D, where the program team could experiment with different layouts and material flow strategies. Also, if additional assembly capacity was needed in another department, it was quick and easy to move workstations from area to area.

- *Production status boards :* It would seem like a simple concept, but it was only observed in practice at program E. At this facility production requirements and real-time status was communicated via a highly visible but low-tech production status board. The board was sectioned off by the different operations in the factory area, and a card for each unit in production was placed in the appropriate zone of the board. In this manner the board provided accurate information of where products were in the process. The board also showed the requirements for each day and for the week so that floor personnel could manage the flow of production themselves. Everyone could see if units were being held up in a particular operation, or if not enough of the needed products were being produced.

- *Production Run Rules* : To avoid miscommunication within a production department at program E, "run rules" were established to guide operators in their daily decisions. It was a way of presenting a simplified scheduling policy and was understood to be the law of the factory floor. To issue an exception to a run rule required approval by a planning team that consisted of the materials planner, the production manager and a floor supervisor.  Examples of rules in this simplified scheduling policy include:

- “Only 100% completed kits will be used for production”
- “Kits will be worked on only in first-in first-out order”
- “When all your WIP is depleted go to your supplier and see if you can help”

The rules established would, of course, be different from company to company.  The important lesson, however, is that amidst the chaos of daily production, it is very helpful to have a simple decision algorithm by which workers can make correct choices on their own and under different production circumstances.

· *Training/simulation* :  Another best practice observed was the use of a simulation room to train new operators and to qualify the skills of existing ones.  A workstation in a separate room was arranged to duplicate exactly the set-up in the actual assembly area.  In this training room workers could conduct the exact same operations that would be required in the real production area, but within a supervised and controlled area.  The room was also equipped with interactive training digital media.  Additionally, since this training station was on wheels, it could be easily changed into an actual production workstation if capacity needs required it.

· The reduction of WIP, has been demonstrated to be an effective way of reducing production cycle time.  This was demonstrated in numerous examples.  Program D documented an 81% improvement in cycle time and 69% reduction in late deliveries as a result of its 84% reduction in WIP.  In addition, there was a correlation in our data between the level of inventory at a program and the cycle time performance of that program.  This relationship is shown in Figure 36.

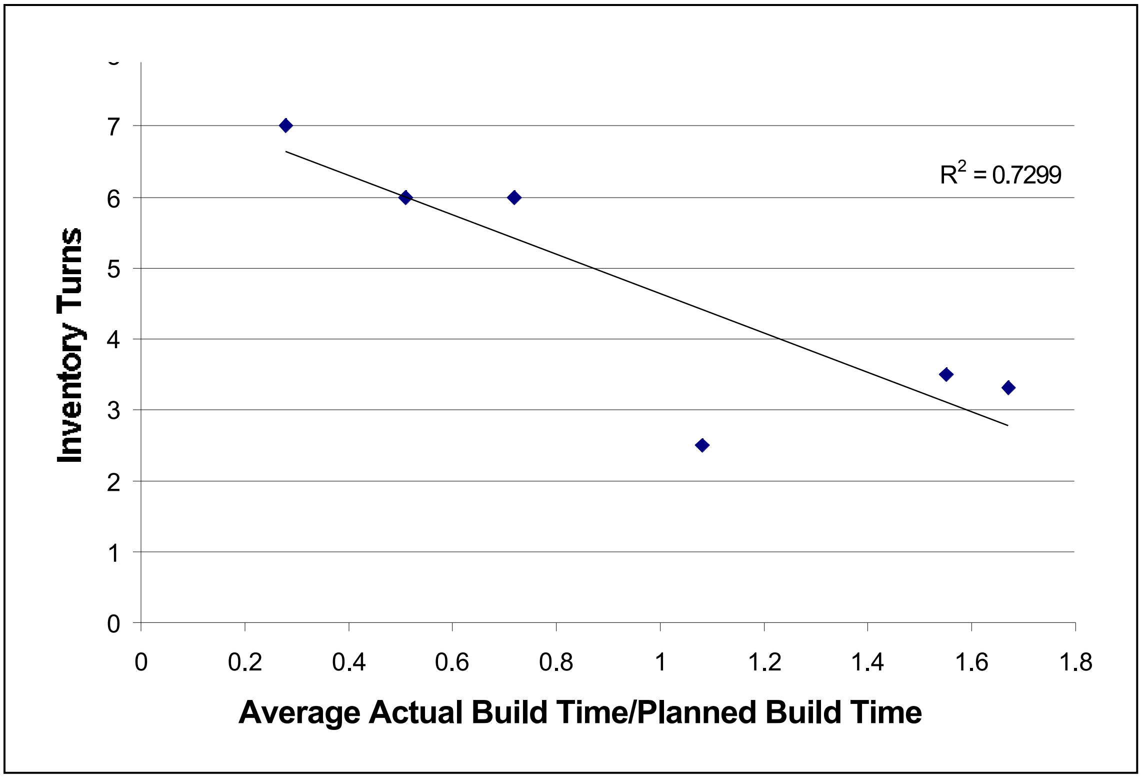


**Figure 36: Inventory vs. Cycle time performance**

### *5.4 Testing*

The testing operations at the sites visited varied significantly because of the variety in products and applications in this study. However there were some good practices observed which could be shared with any testing process to improve the utilization of this often-times bottleneck operation.

- *Equipment Maintenance* : Perhaps the more obvious solution is to have a disciplined schedule of preventive maintenance on test equipment. This is especially true when it comes to calibration. One will recall that a top reason for delay in this study was test equipment issues, in particular, equipment which could not accurately test a product and was consequently giving false-negative or false-positives as test results. An effective way to deal with this was accomplished by program B. There was a strict maintenance schedule, which was understood to be important by all factory personnel. As a result, there had been no equipment in out-of-calibration conditions for several years.

- *Engineer “on-call”* : To provide a quick response to any problems with test equipment program E created a schedule of “technicians on-call” who could be contacted during their call shift, in the event of any testing problem and would provide quick response assistance to resolve the issue and get the operation on track again.

In general, there was extensive documentation on various aspects relating to the testing processes, such as test results, reasons for test failure, equipment diagnostic data, root cause analyses of test failures, and trends of product failures. This data would be examined extensively to keep this critical process closely under control.

### *5.5 Other System Characteristics*

Throughout our research, we gathered information on various aspects of the production systems studied, which fall into categories outside of those previously outlined. There were also practices observed in these subsequent areas which merit mention as they were perceived to also have a positive effect on system performance.

- *Lean performance-based pay* : Although every program used a wide variety of metrics in their organization, there was only one site which actually tied the compensation of their employees to the performance level which was reached on those metrics. Program F, used a two-tiered pay structure in which a large portion of compensation consisted of a base hourly rate and a then a lesser but still significant portion of about 20%, was based on a bonus which was directly tied to the factory operating metrics. These factory metrics included average cycle time, assembly defects, absenteeism, and on-time delivery . This pay structure had been in place for several months and was voted on by the entire workforce. Under this new pay structure there was an opportunity to make significantly more than with the old structure, but there was also the opportunity to end up making less than before, if performance objectives were not met. Upon implementing this system there was a clear improvement in virtually all the metrics included in this measurement system, especially in that measure which is most critical for our study, cycle time. It was observed that typically those metric systems which are directly linked with compensation are the most effective in reaching a mutually agreed upon desired outcome.

- *Self-directed teams* : Program F also operated using self-directed factory teams, which managed their own production requirements and performance. Regular meetings would be held to monitor scheduling, area inventories and of course progress towards the key metrics. Metrics were posted and monitored in the production area, so that there was a clear understanding of how the group's effort and behavior over time affected factory performance and their own pay.

- *Co-located process teams* : In an effort to improve inter-departmental communication, and manufacturing support staff response time, program E implemented co-located engineering teams. Process engineers were moved physically next to the actual areas of production. This change was perceived to have a positive effect on their ability to resolve problems and manage engineering changes, but the change had only recently been implemented. Consequently, data was not available to support the perceptions of improvement.

- *IT system* : Program B had an extensive and elaborate information network across its entire organization that allowed detailed tracking of orders in production. Every workstation was equipped with a computer and bar code reader that was used to document every step of the production process. Through this system the burden of documentation was greatly reduced. In addition, the amount of data available for analysis of their production system was extensive and accurate.

- *Supplier management* : The most intensive supplier management system was observed at program A. There were clear expectations established around a supplier's:
    - Technology developments
    - Quality
    - Working relationship strategies

- Responsiveness
- Delivery
- Cost improvements
- Environmental responsibility

Each one of these dimensions had an extensive set of metrics and specified objectives for each supplier. There were metrics that also directly improved the performance of the producer, such as reductions in cycle time and flexibility to changing supply requirements. The hurdle for what was an acceptable supplier based on these parameters was also periodically raised. The objective was to continuously select fewer but better suppliers who would get increased allocations of business.

These are some relevant examples of ways participants of this study are designing different aspects of their manufacturing system to improve overall performance. Each manufacturer would benefit in understanding the discrete composition of its complete value-chain design and how lean manufacturing practices are applicable in each of these production components. Lean principles not only apply on the plant floor but must also be applied in the product development group, in the human resources department and even on the desk of the financial officer.

### 6.0 Lean Enterprise Model Comparison

The Lean Enterprise Model is a framework used throughout the Lean Aerospace Initiative as a roadmap towards the implementation of lean manufacturing systems and is based on the principles of waste minimization and responsiveness to change. The complete LEM consists of 12 overarching practices which address the entire value chain of a manufacturing organization including the various production system activities of human resources, information systems, product development, cost management, engineering, and procurement. Within each category of overarching practices there are also a series of enabling practices which more specifically outline the modes of operations which are characteristic of lean systems. The LEM also has metrics that provide a reference for LAI members to identify and asses the leanness of their organization and processes, many of which were used in the process of collecting data for this study. In addition, the LEM is used to organize and communicate the work done through LAI to consortium members through a database that is populated with research products such as case studies, surveys, and theses.

Early in this project a LEM survey was constructed to serve as an aid in evaluating the operations and policies of the participating sites. The survey consisted of an abridged set of the LEM overarching practices and measures, and included those that we felt were most relevant for the focus of this study. Subject-matter from overarching practices 5 and 7, which cover product development and client relationship management were not included, as these topics were not within the scope of this research. The survey used a three-rating point system that operated as follows:

**X** = Full implementation of the enabling practice

***/*** = Partial implementation of the enabling practice

**O** = No observed implementation of the enabling practice

The LEM survey was useful in providing a standard base of comparison between facilities. All the surveys were completed by the same researcher to avoid possible variation between leanness perspectives of different surveyors, and each observation of an implementation was documented with the evidence supporting this judgement. Figure 37 shows the score for each program. There was a relatively narrow distribution of scores ranging from 50 to 65, with programs B and D close together in the lead. Tables 3 a-j show a summary of the surveys results.

It was also reassuring that the results from the surveys, which were completed prior to any data analysis showed a strong correlation with the critical lean metric of on-time delivery. This relationship is illustrated in Figure 38.

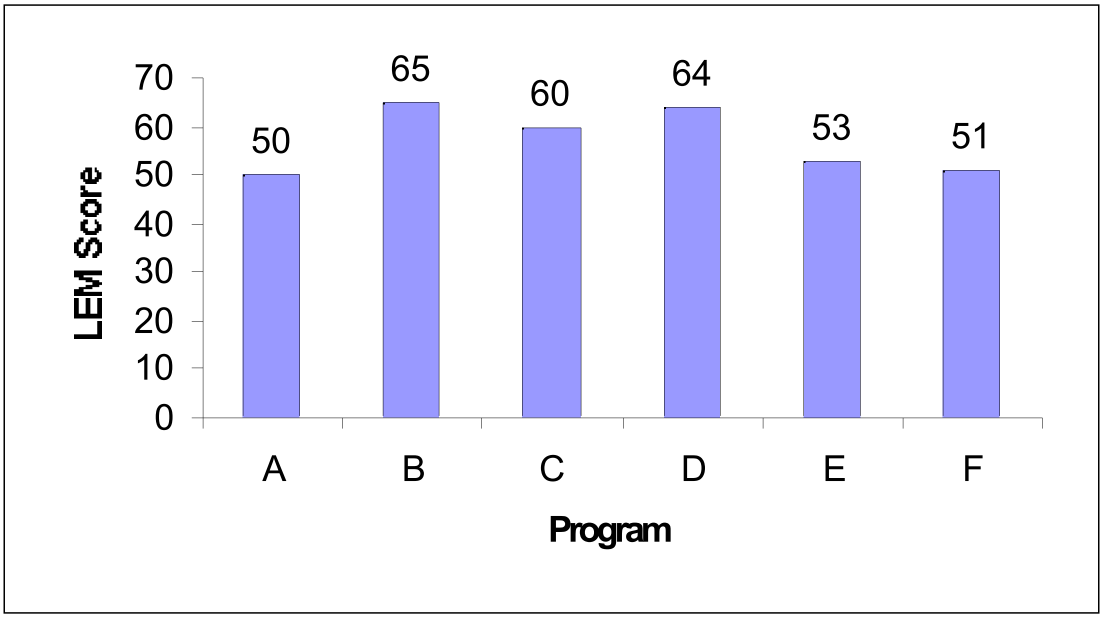


**Figure 37: LEM score by program**

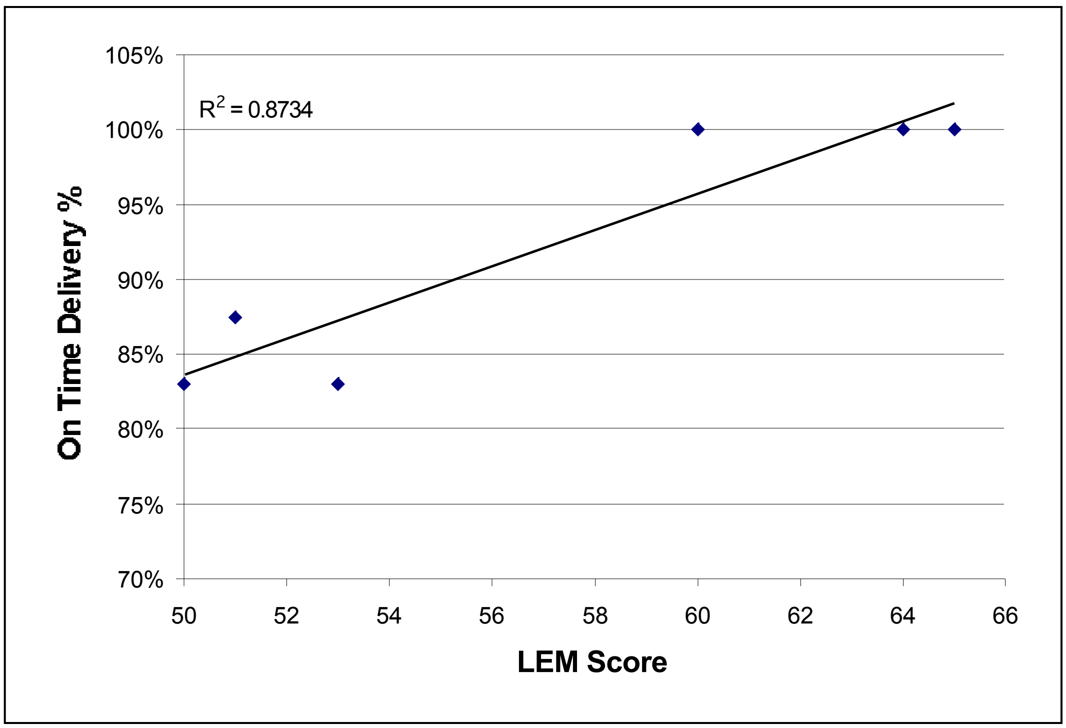


**Figure 38: On time delivery vs. LEM score**

**Table 3a Overarching Practice 1- Identify and Optimize Enterprise Flow**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Establish models and/or simulations to permit understanding and evaluation of the flow process | / | X | X | X | X | / |
| Reduce the number of flow paths | / | X | X | X | X | / |
| Minimize inventory through all tiers of value chain | / | X | X | X | X | X |
| Reduce setup times | X | X | O | O | X | / |
| Implement process owner inspection throughout the value chain | X | X | / | / | X | X |
| Strive for single piece flow | / | / | / | X | / | / |
| Minimize space utilized and distance traveled by personnel and material | X | / | X | X | / | / |
| Synchronize production and delivery throughout the value chain | / | X | / | X | X | / |
| Maintain equipment to minimize unplanned stoppages. (TPM) | / | X | X | X | X | / |

**Table 3b Overarching Practice 2 - Assure Seamless Information Flow**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Make processes and flows visible to all stake-holders | / | / | X | X | / | / |
| Establish open and timely communications among all stakeholders | / | X | X | X | X | / |
| Link databases for key functions throughout the value chain | O | X | O | O | X | O |
| Minimize documentation while ensuring necessary data trace-ability and availability | / | X | X | X | X | X |

**Table 3c Overarching Practice 3 - Optimize Capability and Utilization of People**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Establish career and skills development programs for each employee | X | X | X | X | X | X |
| Ensure maintenance and upgrading of critical skills | / | X | X | X | X | X |
| Analyze workforce capabilities and needs to provide for | O | X | X | X | X | X |

| | | | | | | |
|---|---|---|---|---|---|---|
| balance of breadth and depth of skills/knowledge | | | | | | |
| Broaden jobs to facilitate the development of a flexible workforce | X | X | X | X | X | X |

**Table 3d Overarching Practice 4 - Make Decisions at Lowest Possible Level**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Establish multi-disciplinary teams organized around processes and products | / | X | X | X | X | X |
| Delegate or share responsibility for decisions throughout the value chain | / | / | X | X | / | X |
| Empower people to make decisions at the point of work | X | X | / | / | X | X |
| Minimize hand-offs and approvals within and between line and support activities | O | / | O | O | / | / |
| Provide environment and well-defined processes for expedited decision making | X | / | / | X | / | / |

**Table 3e Overarching Practice 6 - Develop Relationships Based on Mutual Trust and Commitment**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Establish labor-management partnerships | / | / | / | / | / | / |
| Strive for continued employment or employability of the workforce | / | O | X | X | O | / |
| Provide for mutual sharing of benefits from implementation of lean practices | O | O | / | / | O | X |

**Table 3f Overarching Practice 8 - Promote Lean Leadership At All Levels**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Flow-down lean principles, practices and metrics to all | / | X | / | / | X | / |

| | | | | | | |
|---|---|---|---|---|---|---|
| organizational levels | | | | | | |
| Instill individual ownership throughout the workforce in all products and services that are provided | / | / | / | / | / | / |
| Assure consistency of enterprise strategy with lean principles and practices | / | / | X | X | / | X |
| Involve union leadership in promoting and implementing lean practices | N/a | n/a | O | O | n/a | n/a |

**Table 3g Overarching Practice 9 - Maintain Challenge of Existing Processes**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Establish structured processes for generating evaluating and implementing improvements at all levels | / | / | X | X | / | O |
| Fix problems systematically using data and root cause analysis | X | / | X | X | / | X |
| Utilize cost accounting/management systems to establish the discrete cost of individual parts and activities | / | / | O | O | / | / |
| Set jointly-established targets for continuous improvement at all levels and in all phases of the product life cycle | / | X | X | X | X | O |
| Create incentive initiatives for beneficial innovative practices | / | / | / | / | / | O |

**Table 3h Overarching Practice 10 - Nurture a Learning Environment**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Capture, communicate and apply experience generate learning | / | O | / | / | O | O |
| Perform Benchmarking | O | X | X | X | X | / |
| Provide for interchange of knowledge from and within the supplier network | / | / | X | X | / | O |

**Table 3i Overarching Practice 11 - Ensure Process Capability & Maturity**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Define and control processes throughout the value chain | / | X | X | X | X | / |

| | | | | | | |
|---|---|---|---|---|---|---|
| Establish cost beneficial variability reduction practices in all phases of product life cycle | / | O | O | O | O | / |
| Establish make/but as a strategic decision | / | X | O | O | X | O |

**Table 3j Overarching Practice 12 - Maximize Stability in A Changing Environment**

| ENABLING PRACTICE | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| Level demand to enable continuous flow | / | X | X | X | X | X |
| Minimize cycle-time to limit susceptibility to externally imposed changes | X | X | / | / | X | X |
| Structure programs to absorb changes with minimal impact | / | / | / | X | / | / |
| Establish incremental product performance objectives where possible | X | X | O | O | X | O |
| Program high risk developments off critical paths and/or provide alternatives | / | X | O | O | X | / |

## 7.0 Conclusions

The purpose of this study was to provide information that could help improve the leanness of aerospace manufacturers. As was stated at the beginning, the nature of the programs involved in this study allowed us to gain insights into system design effects across the sector as well as at the level of the individual firm. Let us now review our findings by these classifications.

### *7.1 From the sector*

Despite the wide variety of products studied, there were patterns in our data across the sites and programs. From a total of 25 factors examined at each facility, the strongest relationships uncovered are shown in the following table, which describes one factor on the left hand column and its correlation with the second factor on right hand column.

| Factor A behavior | Corr. | Factor B behavior |
|---|---|---|
| Increased build time | 0.92 | Increased process complexity |
| Decreased Inventory | 0.85 | Decreased cycle time performance |
| Less cycle time variance | 0.90 | Better MRP performance |
| More engineering traffic | 0.98 | Increased product complexity |
| Increased test yields | 0.80 | Reduced cycle time |
| Increased throughput yield | 0.78 | Improved on-time delivery |
| Less process defects | 0.97 | Increased test yields |
| Increased test station uptime | 0.80 | Improved throughput yields |
| Increased supplier certification | 0.88 | Decreased supplier delays |
| Higher LEM score | 0.92 | Higher on-time delivery |

**Table 4: Key Relationships from findings**

In addition to these relationships, the following observations were made about sector behavior:

- There is no clear link between external on-time delivery and the management of deliveries internally. Consequently, although delivery performance to final customers was generally favorable in this sector, there were still significant improvement opportunities in smoothing flow throughout the supply chain.

- Cycle-time performance varied significantly in this sector, however typically those sites which had the best on-time delivery also incorporated a significant amount of lead-time buffer into their delivery schedules or had a larger inventory buffer to protect against these internal disturbances.
- There are some clear differences between the defense and commercial sectors, starting with the stability of orders. Given the longer-term contracts in the military, the quantities expected for delivery are typically set far in advance, unlike commercial accounts where the customer base is much larger and orders therefore fluctuate much more.
- There are both similarities and differences in the sources of delays between the commercial and defense sectors. Whereas delays caused by components in the test phase was a common occurrence for both sectors, part availability and delays caused by engineering evaluation were more common in defense and delays due to forecast inaccuracies were more common on the commercial side. This stems from the differences in system design, since commercial programs have a tendency to build to a forecast rather than build to order, which as always the method used in defense.
- Test yields have a significant impact on system performance. Failed products have a very detrimental effect on the flow of production since it places increased burden on resources and introduces delays through engineering evaluations and rework efforts.

### *7.2 From the producer*

Correlation's are useful in identifying simple directional affinities but do not establish causality in these associations. To better understand the causal relationships which exist, we look towards the information collected at the level of the individual firm and examine how changes in individual system designs have had a direct effect on system outcomes. To this end, we have observed the following relationships at one or more (the quantity is noted in parenthesis) of the participating sites in our research.

- (2) Reducing WIP reduces cycle time and variability in the production flow
- (1) Linking company metrics directly to worker compensation is an effective incentive for production performance improvement
- (3) Improving test yields can help improve throughput performance
- (2) Defect reduction efforts are effective in improving test yields
- (1) Coupling operations through the use of kanban can decrease WIP and improve MRP performance
- (1) Workstation arrangements can help improve assembly quality and process ownership
- (1) Program material managers can be more effective at coordinating material requirements than commodity managers who are responsible for several programs
- (2) Co-located manufacturing engineering staff improve response time to production problems and help reduce delays in production
- (1) ESD prevention, compliance and equipment can significantly reduce circuit board defects
- (1) Formal and simple scheduling policies reduce miscommunication and the delays caused by incorrectly prioritized work.
- (1) Increasing supplier accountability for quality and delivery permits deliveries directly to the point of use, which decreases dock-to-stock time and helps reduce over all cycle time
- (1) Local warehouses can decrease inventory and part cannibalization

Finally, a key finding in this study has been that the most significant contributing factor to disrupting throughput in the electronic sector is the quality of the circuit boards that are being brought into the process. This factor influences many of the reasons for delays brought up in the interviews and uncovered in the data. There are cost limitations however to the levels of reliability which are feasible and the highest leverage points to improving this factor are different and need to be determined by each manufacturer. In addition, it has been observed that the Lean Enterprise Model is an effective measure of overall system “Leanness”, which can have a direct impact on producer delivery and responsiveness, and should be used as a roadmap by aerospace manufacturers in reaching their Lean objectives.

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