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Factory Flow Benchmarking Report

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Abstract

The Lean Aircraft Initiative benchmarked representative part fabrications and some assembly operations within its member companies of the defense aircraft industry. This paper reports the results of this benchmarking effort. Comparisons are made using an efficiency metric called flow efficiency. Flow efficiency is defined as the ratio of the fabrication time to the cycle time. In addition, this report explores the major components of the cycle time: fabrication time, lot process delay, storage delay, and transportation delay. The report concludes that the major portion of the cycle time in this industry is storage delay and points out the opportunity to improve cycle time drastically by reducing the amount of storage delay being experienced in the fabrication of products.

Acknowledgments

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I would like to acknowledge the guidance and review of this work by Professor Tim Gutowski. Other contributors of information were Assistant Professor Dave Cochran, Vicente Reynal and Auston Kilpatrick who provided information to determine flow efficiencies in commercial companies.

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List of Abbreviations

CNC	Computer Numerical Control
CRT	Cathode Ray Tube
d.p.m.o.	Defects per million opportunities
d.p.u.	Defects per unit
I. E.	Industrial Engineering
MIT	Massachusetts Institute of Technology
MRB	Material Review Board
MRP	Materials Requirements Planning
MRP II	Manufacturing Resource Planning
PWA	Printed Wiring Assembly
SPC	Statistical Process Control
WIP	Work In Process

1. Executive Summary

The Lean Aircraft Initiative is a research effort to study the defense aircraft industry to define and help implement road maps for fundamental change in both industry and government operations, based on best lean practices. The goals of this effort are to achieve greater affordability of systems, increase efficiency, attain higher quality, enhance technological superiority and build a stronger U. S. defense aircraft industrial base. One step in the achievement of greater affordability and efficiency is to reduce the time it takes to produce a product.

The time it takes to produce a product can be thought of as the product cycle time. In commercial industries a significantly better product development time has been a strategy for competitive advantage. There are a number of components of cycle time broadly grouped into development and production cycle times. The latter component captures the time it takes to produce that product. The cycle time to produce a product is a major research focus area of the Factory Operations Focus Group in the Lean Aircraft Initiative. This study collects data on specific parts that are produced in the defense aircraft industry to characterize the production cycle time component of cycle time.

The Lean Aircraft Initiative Factory Operations Focus Group conducted a benchmarking effort with members of the consortium during 1995-1996. The major objective of this research was to characterize the flow of products in the fabrication process.

Member companies divided by three sectors (airframe, electronic and engine) determined the method of accomplishing this research and the data that could be collected. Part characteristics were defined so that they were essentially similar between each company (within a given sector) so that each company agreed that the variance in the results gathered on this part were due to the characteristics of the system not the characteristics of the part. The members picked parts that were representative of the sector. Although information on part differences was collected, it was found that the average time spent on part fabrication or assembly time was less than 15 percent of the cycle time for all parts and less than 5 percent for most parts. Therefore, it was assumed that part differences had relatively little impact on the benchmarking results. In some but not all cases, an assembly in addition to a part fabrication was selected for study.

A questionnaire was developed to gather the data. There were 17 respondents to the questionnaire from all sectors. Initial data reduction indicated data inconsistencies that required an extensive data verification effort. Telephone interviews and on-site verification of data was used to resolve the data inconsistencies. Once a consistent set of data was obtained, an analysis was completed.

The major elements of the data collection effort centered on the time it takes to actually fabricate a part compared to the time the part was in the system for fabrication. Time to fabricate a part was approximated by actual labor hours. We took into account the differences in the number of shifts and the duration of the shifts between respondents. Besides displaying the raw data a normalized factor called flow efficiency was calculated as a ratio of actual labor hours per part to total cycle time the part was in the system. The analysis revealed that the largest component of the cycle time was waiting time. Where waiting time is the time the part is waiting as it goes through the fabrication process. In the airframe sector and engine sector, the proportion of cycle time that the product was waiting was 96 and 87 percent respectively. In the electronic sector, it ranged from 25 percent to 98 percent. In a lean production system, the amount of wait time would be reduced to the lowest level possible. From our knowledge of other industries, much effort is expended to reduce this wait time to zero so that the flow efficiency can approach a value of 1.0.

The analysis of the data revealed that the airframe sector had flow efficiencies from 0.02 percent to 0.8 percent, the electronic sector from 0.02 to 18.7 percent and the engine sector from 0.7 to 13 percent. If a 100 hour cycle time is assumed then the product is actually being fabricated only 18.7 hours in the best case (flow efficiency of 18.7%) and in the worst case of only 1.2 minutes (flow efficiency of 0.02%).

We hypothesized and supported with correlation analyses that there would be higher flow efficiencies with lower lot sizes and higher flow efficiencies with shorter distance traveled. The flow efficiency, at its best, will vary inversely with the lot size. We saw that there were no flow efficiencies above 2 percent if the parts traveled more than 2000 feet. We also found that the type of process layout had a great deal to do with the flow efficiency. Job shop layouts did not achieve above 0.1 percent flow efficiencies while flow shops, cells or dedicated lines were able to achieve values as high as 18.7 percent flow efficiencies.

A limited amount of benchmarking was accomplished in commercial companies using the same flow efficiency metric. It was found that considerably better flow efficiencies of greater than 50 percent are achieved with manufacturing or assembly cells. We also found that similarly low flow efficiencies are realized despite the high production volume if batch production processes are used in a job shop process layout. The challenge to the defense aircraft industry is to create process layouts that enable the higher flow efficiencies despite the relatively lower volumes.

In the questionnaire, several other areas were collected: router queuing time, process control methods, quality information, equipment uptime, worker training, operator inspection, employee suggestions, facility data and in the electronic sector time to create / modify work instructions. This latter category revealed that the time to create work instructions averaged about 7 to 17 hours per hour of standard work to be performed. These values differed due to difficulty of the work instruction set.

In the airframe sector, information was gathered on the time between the generation of the work order and the start of work on the work order (router queuing). The median values for this router queuing ranged from 11 to 32 percent of the cycle time. The maximum values for this router queuing time was as high as 83 percent of the cycle time. These high values would suggest that the scheduling system is dysfunctional. We also found that the distances traveled by the parts were also quite high averaging from 2416 to 5023 feet. Steps with process control ranged from a low of 9.3 percent to a high of 81.4 percent and averaged from 44 to 55 percent. The predominant process control method (at about 80 percent) was process verification consisting mostly of manual inspection. Statistical process control (SPC) was used for process control in about 16 percent of the process steps. Although not all respondents reported quality information, we were able to gather some information on defects per standard hour yielding averages of .22, .04 and .24 for extrusions, brake-formed parts and machined parts respectively.

In the electronic sector, the distance the parts traveled was the smallest of the three sectors averaging about 600 feet for PWAs and chassis, and less than 300 feet for cables/harnesses respectively. We asked and were provided information about equipment uptime and found it averaging 93.5, 96.8 and 98.6 percent for the PWAs, chassis and cable/harnesses. Responses to questions about worker training documented about 50 to 60 hours of skill training per year. This sector provided the most information on quality. The average values of hours of rework compared to actual manufacturing hours yielded 11 percent for PWAs and 7 percent for chassis and cables/harnesses. Operators inspected a large portion of their work showing median values of 85, 98 and 99 percent for PWAs, chassis and cables/harnesses. The percentage of employee suggestions implemented was 78, 80, and 56 percent for PWAs, chassis, and cables/harnesses. This resulted in an implemented suggestions per employee average of about 8 percent.

In the engine sector we did not get sufficient usable responses to display sector results regarding flow efficiencies, however we were able to use the data in combination with the other sectors in our flow efficiency analyses. This sector used cells and flow shop layouts most prevalently. We were able to show process and factory layout characteristics for this sector. About a third of the processes used to make turbine disks use CNC equipment and when SPC is used it is used in about one third of the process steps. This sector uses very little facility space for WIP storage and specific areas for rework or repairs.

One principle of a lean production system is waste minimization. The time that a product sits without value being added to it is waste. Therefore, lean production systems will have little wait time as the product goes through the production system. One of the major objectives of the Lean Aircraft Initiative is the reduction of cycle time. From our research, the largest component of that cycle time is wait time. Therefore, the most impact on cycle time reduction will come from wait time reduction. In order to accomplish wait time reductions, it is necessary to know product actual cycle time and to understand the components of this cycle time. If the major contributors to wait time can be determined, then process improvement efforts can be initiated to reduce or eliminate the wait time causes.

2. Introduction

2.1 Benchmarking Objectives

One of the tenets of lean production is the minimization of waste. In the production of products, one element of waste is the time that no value is being added to a product. Therefore, a lean production system would be characterized with operations that add value to the product for most of the time the product is in the production system. As a product is produced it flows through the factory from one operation to the next until the manufacture of the product is completed. If a product is being worked on continuously in the production system, it is flowing from one operation to the next with no (or little) wait time between operations. An objective is to optimize this flow of products through the production system. Therefore, in an optimized production system, the amount of wait time between operations is reduced to as low a value as possible.

A factory will have any number of products being produced within the factory and each product will have many constituent parts. In order to optimize the production system, the individual parts of the products have to be optimized. One way to consider this problem is to picture the flow of these parts as they are being fabricated. Then each part describes its own path through the production system. In each of these paths, the objective is to optimize the flow by reducing the non value added time between each operation in the flow path. There are many practices which will enable this optimization of product flow throughout the production system. From our work on the Lean Enterprise Model, we have hypothesized that some very important enablers are:

- Establish models and/or simulations to permit understanding and evaluation of the process flow
- Reduce the number of flow paths
- Minimize inventory through all tiers of the value chain
- Reduce the setup time
- Implement process owner inspection throughout the value chain
- Strive for single piece flow
- Minimize space utilized and distance traveled by personnel and material
- Synchronize production and delivery throughout the value chain
- Maintain equipment to minimize unplanned stoppages

How well the product flows through the factory can give a sense for the efficiency of the production system. The more efficient production systems would have production cycle times to fabricate and build their products only slightly more than the sum of the individual operation processing times. With this concept in mind, it is possible to estimate the efficiency of the production system by monitoring the efficiency of individual product parts produced in the fabrication process. If representative parts can be chosen to obtain data on their flow characteristics important information can be obtained about the production system.

In the Lean Aircraft Initiative, one of the expectations sponsor companies have is the gathering of benchmarking information that establishes how member companies perform relative to other member companies and relative to leading companies from other industries. The researchers at the Lean Aircraft Initiative proposed to the Factory Operations Focus Group to benchmark specific parts to be defined by the focus group to get information about member production systems. As a result, the Factory Operations Focus Group developed a plan to benchmark member companies during 1995-1996.

2.2 What was Benchmarked

Since the nature of the products produced is vastly different between the three sectors within the Lean Aircraft Initiative, it was initially thought that an apples to apples comparison could not be accomplished across sectors. Therefore, three separate benchmarking efforts would be necessary. In each of the three efforts, the questionnaire was designed to obtain data on parts or assemblies that were similar (within the sector) as agreed by the sector members. Therefore, each sector needed to choose the part/s that would be representative of the fabrication/assembly operations in their sector.

The Massachusetts Institute of Technology (MIT) research team prepared a strawman list of data it desired to collect. This strawman list was debated in each sector to see what data should and could be collected to support the benchmarking effort. As a consequence, each sector went through a two step process to determine what was to be benchmarked: (1) define the products to be benchmarked in member companies, and (2) what data should and could be collected to support the benchmarking effort. In the sections below the results of these efforts are captured.

2.2.1 Airframe Sector

The airframe sector agreed to benchmark the following parts:

1. Sheet Metal (all pieces less than two feet long and less than 1/4” thick)

    a. Extruded parts consisting of three different part numbers of the “T,” “L,” “C,” or “Z” cross section. Since most of the part numbers chosen will be batched items the data will detail the batch as it progresses through the factory operation.

b. Three different part numbers of a brake formed part. Again the data will detail the entire batch going through the factory operation.

2. Machined prismatic part made on a 3 axis machine with a part dimension of less than one foot cubed. Three separate part numbers will be tracked through the factory operation.

The members of the airframe sector that made the determination of part benchmarking and data collection were:

Fred Stahl, McDonnell Douglas
Don Pope, Northrop Grumman
John Horton, Lockheed Ft. Worth
Don Cook, Beech
Sam Hodnett, McDonnell Douglas
Don Meadows, Lockheed Marietta
Michael Chapman, Boeing
John Klempay, USAF
Facilitator: Tom Shields, MIT

2.2.2 Electronic Sector

The electronic sector agreed to conduct benchmarking in the following common product areas (each company agreed to identify a particular product line in each of these three product areas with an additional stipulation that the production requirement be at least 20 in the last year):

1. Printed wiring assemblies (PWA)

2. Electronic chassis

3. Cable / harness.

The members of the electronic sector that made the determination of part benchmarking and data collection were:

Tom Holcomb, Textron
Gary Stidham, USAF
Jim Everett, TRW
Dennis Jagard, Litton
Charles Hardin, Martin Marietta
Jerry Rosser, Hughes
Damon Osterhus, DSMC (gov't)
Facilitator: Jim Schoonmaker, MIT

2.2.3 Engine Sector

The products that were chosen for study in the engine sector were:

1. The fabrication of a titanium engine disk post ultrasonic through final inspection with a straight dovetail. The engine disk will be normalized by choosing a diameter between 15 and 20 inches which is bolted with no splines.

2. The fabrication of a high nickel alloy annular combustor liner from raw material to final inspection including ceramic coating. Allied Signal will choose a combustor between 16 to 18 inches outer diameter while Pratt and Whitney and GE will pick combustors between 30 to 40 inches outer diameter.

The members of the engine sector that made the determination of part benchmarking and data collection were:

Dave Lowery, Allied Signal
Rob Roark, Pratt and Whitney
Bill Rouse, GE
Facilitator: Tom Shields, MIT

2.2.4 Information Requested

Although there were some differences between the sectors the information gathered was very similar. This information falls into five main areas: manufacturing data, engineering data, facilities and maintenance data, manpower data, and quality data. In general, the information requested was the following:

Manufacturing Data

- Actual manufacturing touch labor hours for each part number chosen
- Actual elapsed cycle time: for the airframe sector - from the printing of the work order until the first operation; for the engine sector - for fabrication operation chosen (20 samples preferred) measured as follows: (1) for the disk, post ultrasonic work order release to the factory through final inspection and (2) for the combustor liner, issuance of work order through final inspection; for the electronic sector - actual elapsed cycle time from the first operation until the part is in stock.
- Number of shifts and duration of each shift
- Number of these part numbers produced per year for past five years (or for as many years as it was in production)
- Batch size (order quantity on the work order) for the parts chosen
- Copy of the work instruction / operation sheet or equivalent for the part chosen
- Distance between process steps over the entire fabrication operation
- Number of pieces of machinery / processing equipment that supports this part
- Number of process steps for which process control or quality data is gathered (including but not limited to SPC data)

- For machining operations in the airframe sector, the number of machines per operator
- For the electronic sector, test hours per area, number of different products produced in the area, work in process levels, and number of machines that are automatic or semi-automatic
- In the electronic sector a separate section was added to capture the actual labor hours required for work instruction creation and the extent of use of paperless technology
- Number of process steps in engine sector that are mechanized (defined as an automated step in which the operator only loads and unloads the part being fabricated and the machine does all operations including inspection)

Engineering Data

- Total number of Industrial Engineering (I. E.) standard hours for the part number chosen
- Sketch or drawing of the part
- Age since last major design revision (can use the revision date from the drawing)
- Number of contract tool part numbers that support this part excluding cutters, etc.
- For machining operations in the airframe sector: number of holes drilled in the machining, linear inches of cutter head travel, number of different setups required, and the setup time
- For the electronic sector specific information on printed wiring assemblies (PWA): board density, total parts/components per PWA, number of unique parts per PWA, and number of connections
- For the chassis assembly in the electronic sector: volume of the chassis, number of parts/components per chassis, number of unique parts per chassis, and number of connections
- For the cable/harness in the electronic sector: the length of the cable, number of wires in the cable, and number of connectors

Facilities and Maintenance Data

- Square footage of the area
- Equipment uptime percentage
- Lost process time due to equipment non-availability

Manpower Data

- Number of employees in the area
- Number of implemented employee suggestions (in last year)
- Skills training hours

Quality Data

- For the area or shop which produced the parts under investigation (i.e. the entire sheet metal shop or entire machine shop) provide the quality measure in use for the entire shop or area. Preferable quality measure would be defects per standard hour or defects per actual hour
- Number of MRB actions during part fabrication
- Defects per unit defined as anything that stops a part from proceeding
- Number of work orders that complete the fabrication operation with no defects (i.e. there was nothing that caused the part to be stopped in its flow through the process)
- Number of mandatory government inspection operations
- Number of parts / pieces that require rework or repair actions
- Number of parts / pieces that are scrapped
- Average time to resolve corrective actions of problems identified
- Top three repeated correction actions and their total numbers

2.3 Methodology

A research design was devised to measure individual operation processing times and production cycle time to obtain a measure of the efficiency of the flow of products through fabrication and some assembly operations in the defense aircraft industry. We also attempted to collect data which would indicate other lean activities.

A questionnaire was the research methodology chosen. Based on the decisions about the benchmarking effort from each sector, a questionnaire was crafted to collect the data elements agreed by the participants in that sector. To develop the questionnaire a sector wide telephone conference was used to fine tune the data to be collected. With this information, a sector pilot benchmarking questionnaire was prepared and tested with a volunteer company. Based on feedback from the pilot questionnaire, the questionnaire was modified for release to the entire sector in the May-June 1995 timeframe. Seventeen companies returned the benchmarking questionnaire. There were seven respondents from the airframes sector, seven respondents from the electronic sector and three responses from the engine sector.

After the questionnaires were returned an initial data analysis was completed. It was noticed that many respondents had provided information that did not make sense when analyzed. Clearly, verification of the data was necessary. A structured checklist was used with each respondent to help identify missing information in the data verification effort.

We prepared packets with the questionable data and faxed this to the points of contact. We attempted to resolve the ambiguities over the telephone. After preliminary phone calls to the companies, as well as mailing the packets to each of the companies stating the deficiencies in the data, it was clear that it would be necessary to make visits to many of the actual plant sites in order to get useful data. This was due to several factors: (1) it was difficult to find the person who had originally filled out the survey in each company, (2) the return time for the follow up packets was excessively long, (3) several misunderstandings regarding questions on the survey could only be eliminated by speaking directly with the company representative.

The original goal was to visit each one of the companies who submitted a survey. This goal was nearly reached, as all electronics sector companies were visited, two of the three engine sector companies, and four of the six airframe sector companies. In these visits, a structured checklist was used to help capture important information. The other plants were consulted by telephone, which succeeded to verify the necessary data points and eliminated most deficiencies. In a few cases, the company could not provide the requested data. These respondents were not included in the analysis. After the verification effort a consistent set of data was available for analysis.

The elapsed cycle time was calculated based on the days the part was in production. This was converted to hours using the number of shifts and the shift duration at each respondent. The data verification effort obtained the number of shifts and the hours allocated to each shift. Any day of the week that was not a work day was not counted toward the cycle time hourly calculation.

The primary research effort was in developing the data for benchmarking the defense aircraft industry but a similar methodology was used to collect data from other industry companies. This information is presented for comparison in the Flow Benchmarking Other Industry section.

3. Benchmarking Results

In the sections that follow the raw results on the parts benchmarked by the questionnaire will be presented for each sector. The information presented is centered on three elements of the data collected from the questionnaire; cycle time, wait time and router queue time. Pictorially, this is displayed in Figure 1. For common understanding of terminology the following definitions were used in this study:

Cycle time (hours) - the total time from initiation of work order to the completion of the manufacturing process and the closing out of the work order.

Waiting time (hours) - the time the work order spends on the floor without work (in labor hours) being charged to the work order. This is not to be construed as resource (human or machine) idle time.

Router Queuing (hours) - the time between creation of the work order and the first operation step for the work order.

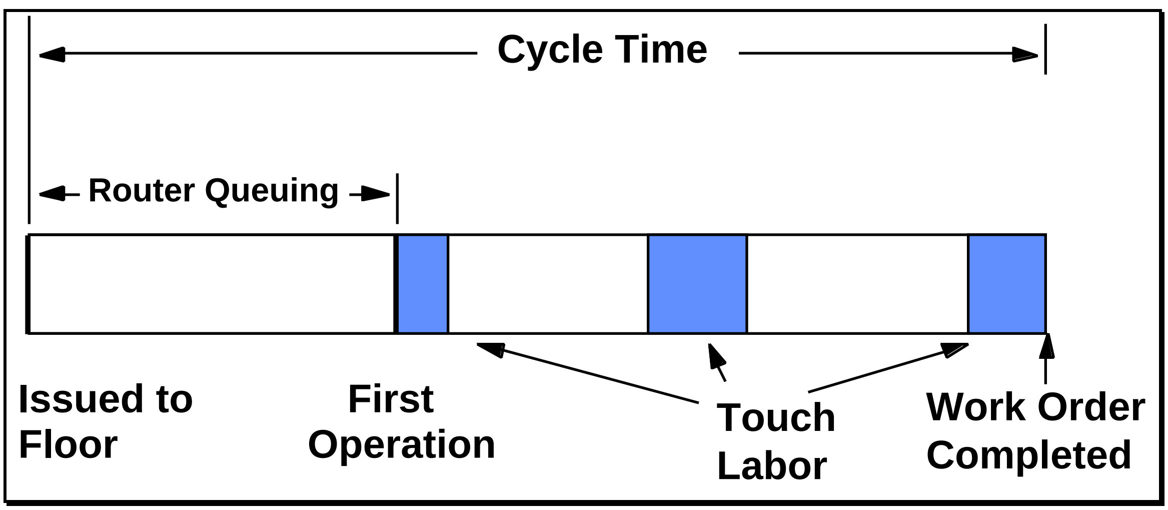

Figure 1: Part Manufacturing Timeline

Each sector did not collect common values for cycle time. Only one sector collected the time from initiation of the work order until first operation, therefore, the most common value to use for cycle time between the different sectors is the time from first operation being performed on the work order until the work order was closed out.

The research team expected each sector's results to be peculiar to that sector because of the different types of parts chosen. In other words, the processing time for the parts would dominate the results and not allow comparisons across sectors. Therefore, each sector's data was segregated and collected separately.

3.1 Data Validity

During the data verification effort several factors were discovered that would lead to misinformation. Since the research effort hinged on the veracity of the time ascribed to the actual cycle time and the actual touch labor time in producing the parts, this information was scrutinized thoroughly. There were found to be two threats to this data, the use of estimates instead of actual data and the use of planned times instead of actuals.

Some companies did not provide actual touch labor time to produce the parts chosen. Instead they provided I. E. standard hours. Although these values are engineered estimates of the time it should take to produce the product, we found that these estimates varied from the actual values by as much as a factor of five. In the data verification effort, we endeavored to get actual touch labor time instead of the I. E. standard hours. If we were not able to obtain this information the data was dropped from the analysis.

In figuring the cycle time, some respondents submitted planned cycle times rather than the actual cycle time as measured from work order documentation. We found that the planned cycle time was significantly less than the actual cycle time recorded by a factor greater than five in those companies that provided us both sets of information. In the display of the raw data that follows, we asterisk the information that is based on planned cycle times for your caution in interpretation. Later in the analysis of the data, we found that the error introduced by planned values forced us to remove any of this data in our correlation analysis.

In the airframe and the engine sectors, the work orders proceeded from operation to operation as a complete work order with one person performing the operation at each step. This type of process flow is depicted in Figure 2 as Process #1. In the electronic sector for the printed wiring assemblies, in particular, we discovered a different work process shown as Process #2 in Figure 2. The work order was for a lot size of x but the work order was broken into smaller “batch sizes” (x/y, were y is the number of batches in which the work order was broken) for processing. Furthermore, it was found that the batch size varied as the product went through the various operations. Therefore, the value of y could not be determined. Another way to approach this dilemma was to determine the number of people that worked on the product when it was broken into these smaller batch sizes. Although this was attempted during the data verification trips, we found that the respondents did not keep this type of information. Therefore, it was possible for the actual touch labor time to be greater than the actual cycle time.

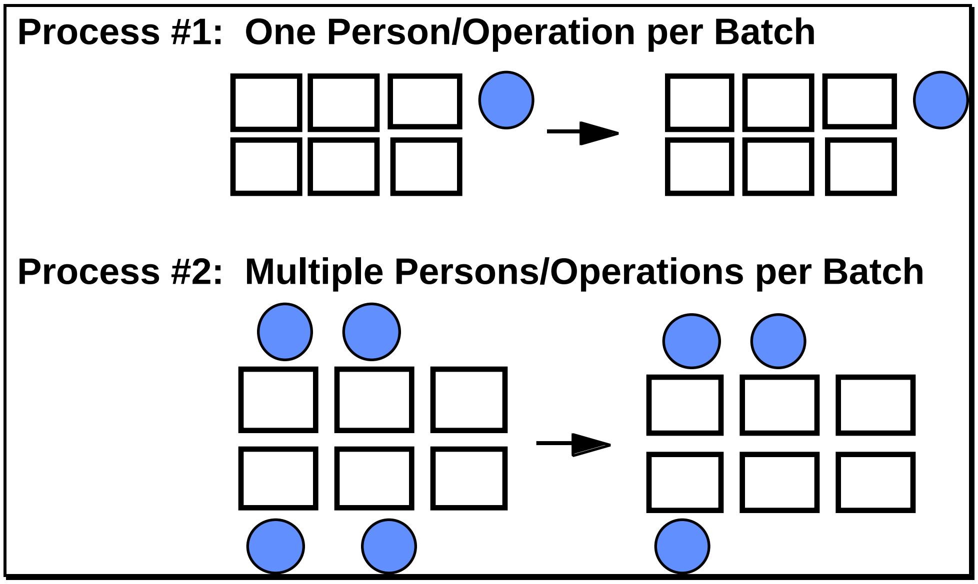

Figure 2: Touch Labor Measurement

To understand how this might happen refer to Figure 3. Let's say that the work order is for a lot size of three, however, the work is processed as a batch size of one. In this three operation process, we can see that there are times when the batch (one item in this case) is being processed simultaneously with other batches. When this happens more actual touch labor (shown here as a single unit per operation) is accumulated than actual cycle time. For this example, the actual touch labor time accumulated is 9 units and the actual cycle time is only 5 units. In the case of our research results, the batch size is unknown therefore the result we saw was the actual touch labor time was greater than the actual cycle time.

This confounding of the lot size information forced us to calculate touch labor on a per part basis to remove the effect of ambiguous processing batch sizes. Therefore, we are providing information with regard to how a single part acts as it flows through the production system. For the cycle time of this part, we used the cycle time of the work order. This approach assumes that the individual part being processed stays associated with its batch and that the batch stays associated with the lot in the work order so that the cycle time of the work order is the cycle time of the part. In most cases that we observed, the parts may have been completed prior to the work order cycle time but the parts were collected as a whole work order before proceeding to the next step. There were instances in which certain parts were culled out of the work order for special handling and this, of course, would yield a different cycle time for the individual part. However, we did not find that using the cycle time of the work order corrupted the analysis because it represented the most common practice. In the presentation of the raw data that follows, we present the entire work order touch labor time where possible (airframe sector only).

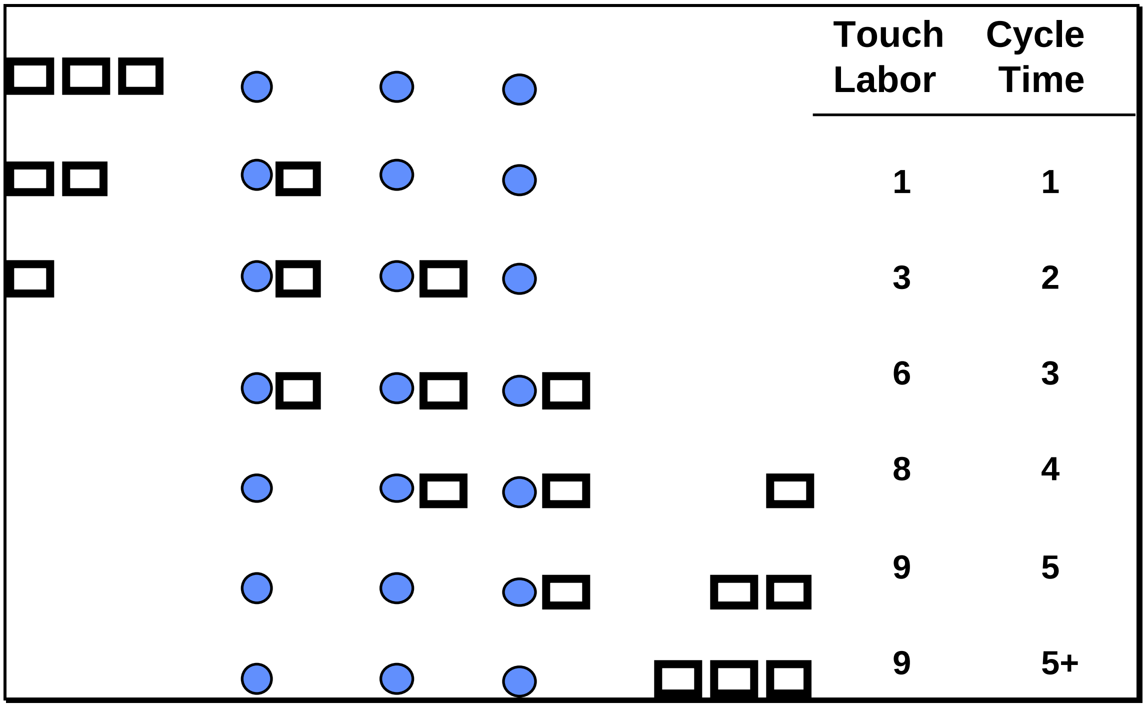

Figure 3: Lot Size Ambiguity Effects

We collected data on multiple work orders for the same part number. We did this to ensure that we were getting consistent data. For each work order, we made our calculations from the data then averaged the results of these calculations to obtain the results for this part. We did this with each respondent and used these values to compare between respondents.

In the questionnaire, we asked some additional questions to explore other lean activities such as distance traveled by the parts, worker skill training, methods of process control, and machine uptime. These questions differed by the sector and will be reported in the sector section that follows.

3.2 Airframe Sector

The following plots (Figures 4-6) contain the usable raw data collected from the seven respondents from the airframe sector. They show the components of cycle time including waiting time, number of touch labor hours and router queuing time. The length of the bar is the total cycle time, which is the sum of the waiting time and the touch labor and the router queuing time. Appropriate exceptions to the data are noted with asterisks.

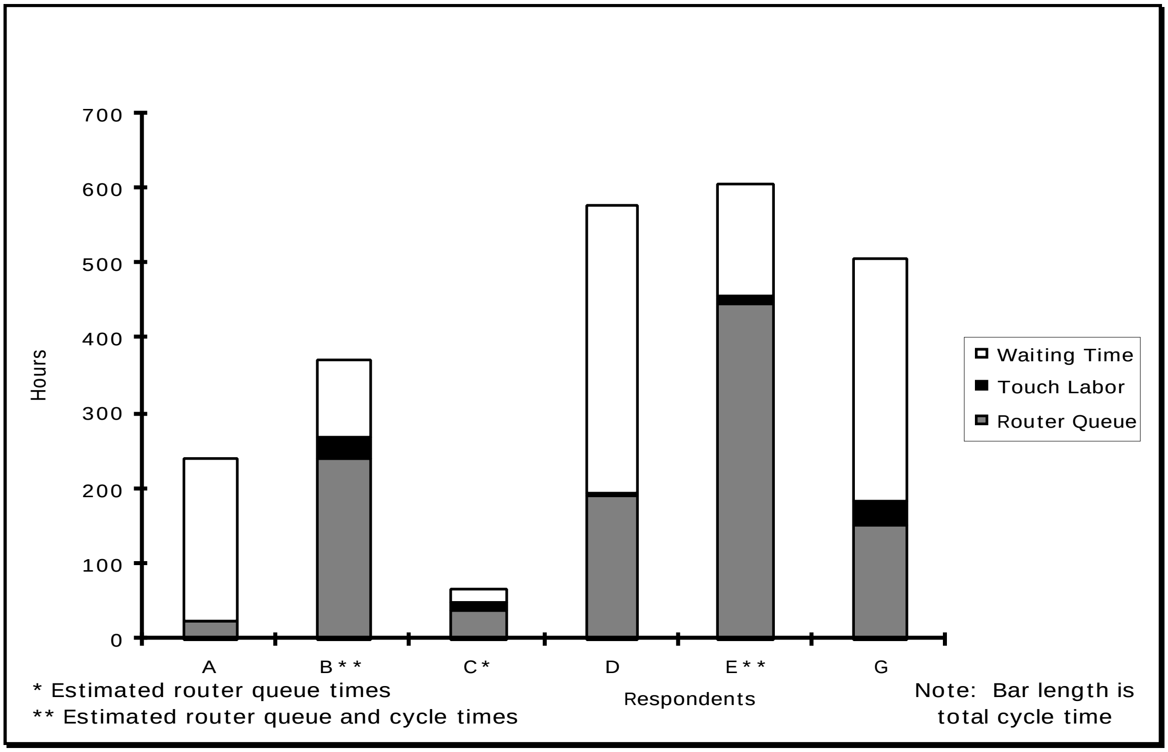

Figure 4: Airframe Sector - Extrusions

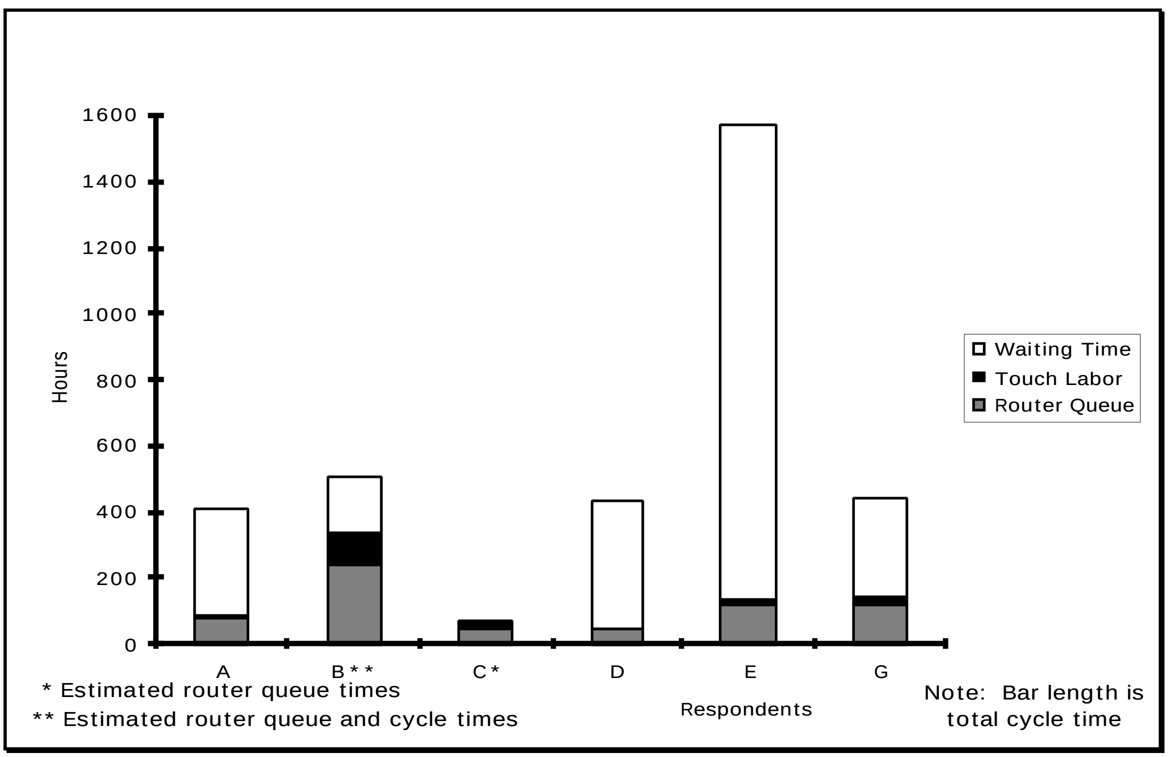

Figure 5: Airframe Sector - Brake-formed Parts

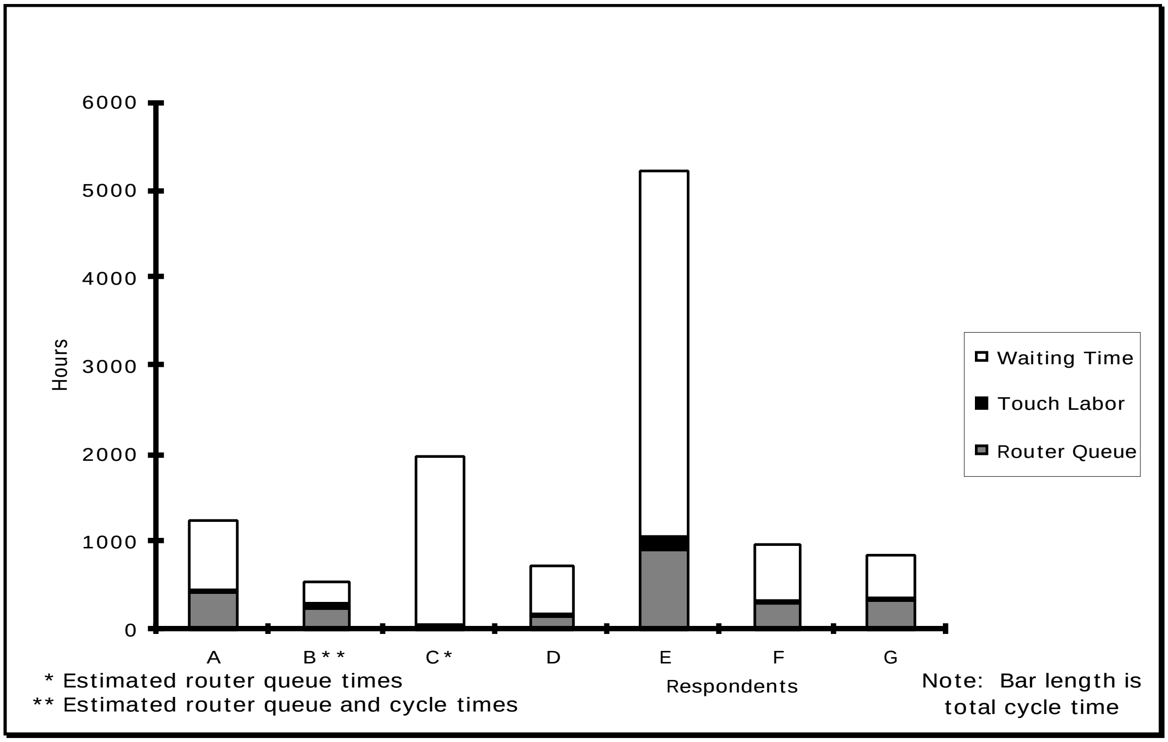

Figure 6: Airframe Sector - Machined Parts

We also captured in the questionnaire the distance traveled by the parts as they moved through the factory. Figure 7 portrays this information on each part provided in the questionnaire.

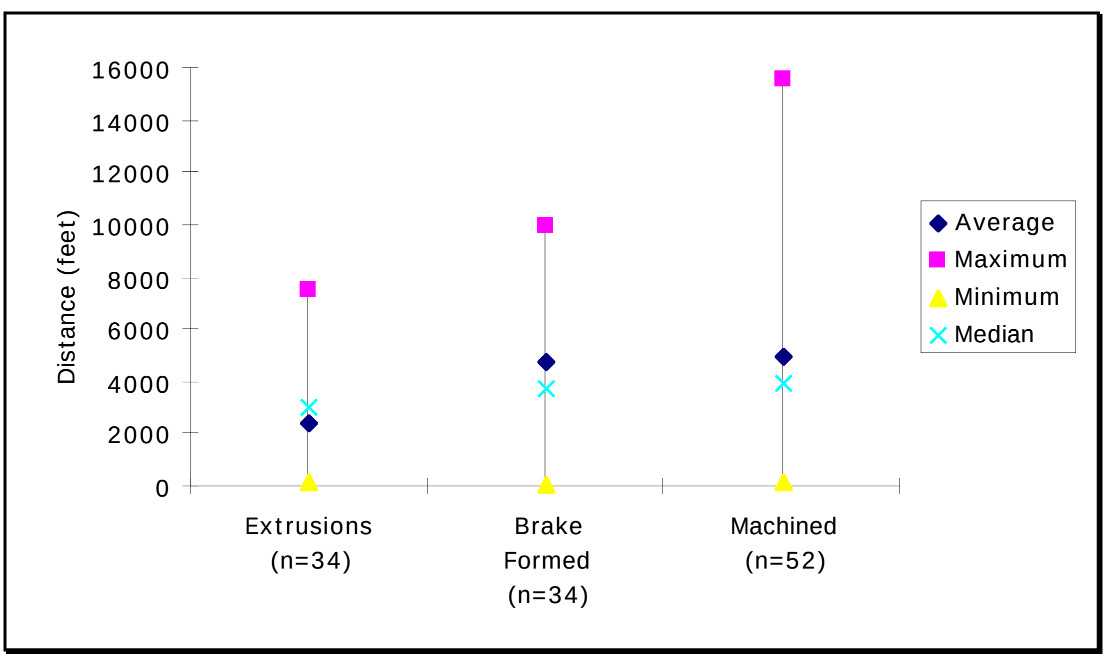

Figure 7: Distance Traveled by Parts Benchmarked in the Airframe Sector

In this sector, we were curious about the process control methods in use. In the questionnaire we asked how many steps of the process to make a part were controlled in some manner. We also asked the respondents to characterize the method used for process control. We gave them five choices: using SPC on variable data, using SPC on attribute data, active feedback (automatic machine control), process verification (visual inspection and attribute measurement without SPC) and an other category. There were no respondents that used active feedback. The table below gives the results of this information using the average values of respondents inputs on the three types of parts, extrusions, brake formed parts and machinings.

		Process Control Method Used		
Respondent	Steps with Process Control (%)	SPC (variable)	SPC (attribute)	Process Verification
	Extrusions			
A	55.1%	16.0%	3.0%	81.0%
E	27.9%	60.0%	0.0%	40.0%
G	17.4%	0.0%	0.0%	100.0%
	Brake-formed Part			
A	44.0%	16.2%	0.0%	83.8%
E	24.2%	60.0%	0.0%	40.0%
G	19.6%	50.0%	0.0%	50.0%
	Machined Part			
A	43.9%	16.9%	0.0%	83.1%
D	81.4%	45.8%	0.0%	54.2%
E	47.7%	0.0%	0.0%	100.0%
F	9.3%	100.0%	0.0%	0.0%
G	50.0%	36.1%	0.0%	63.9%

Table 1: Process Control Methods Used in the Airframe Sector

We asked for quality data on the parts selected for benchmarking or in their absence the quality data from the shop in which the parts were fabricated. We were able to convert the data to a defect per standard hour basis. We did not have sufficient data for widespread comparison but the limited data is presented below in Figure 8.

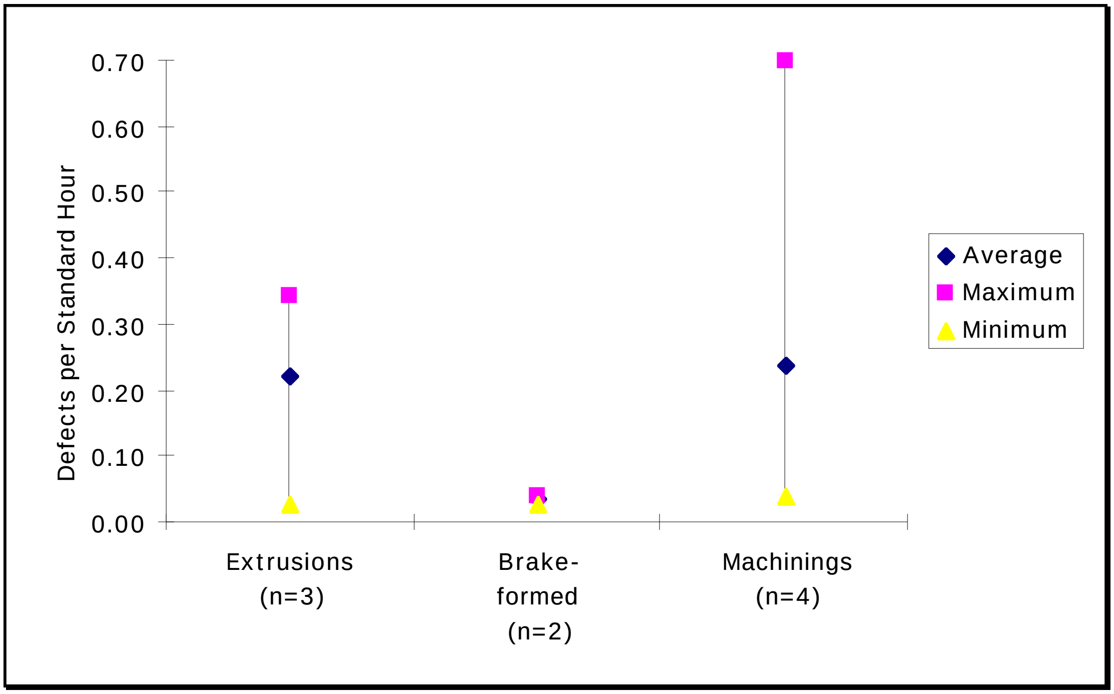

Figure 8: Quality in the Airframe Sector

The airframe sector is the only sector in which router queuing times were collected. This data indicates that in many cases the work order is issued but work is not started for some time. In looking at the three parts benchmarked in the airframe sector in Figure 9, the median router queuing fraction[1] is 32, 11 and 26 percent for extrusions, braked-formed parts and machined parts respectively. The range of these values is astonishing with the maximums in the order of 74, 60 and 83 percent respectively for extrusions, brake formed parts and machined parts. Unsubstantiated inferences could be drawn that the scheduling system is generating work orders for the factory when either the factory is capacity limited or work orders are issued ahead of need (schedule buffer). In the former case, the factory is overburdened and in the latter case the factory is being flooded with work orders. Another explanation could be a management strategy that releases work orders before planning is started. Therefore, router queuing time could also include work order planning. Since the parts chosen were mature parts and operation/process sheets were well established, we did not feel this to be a major threat to our findings. The result is that the shop floor management picks the work orders for execution by some priority or informal decision system. This situation can lead to a large WIP inventories.

[1] Router Queuing Fraction in this case is the fraction of time for router queuing (from the issuance of the work order for the part until the work order was first worked on) compared to the cycle time for processing the part. In this case the cycle time includes router queuing, processing time and wait time.

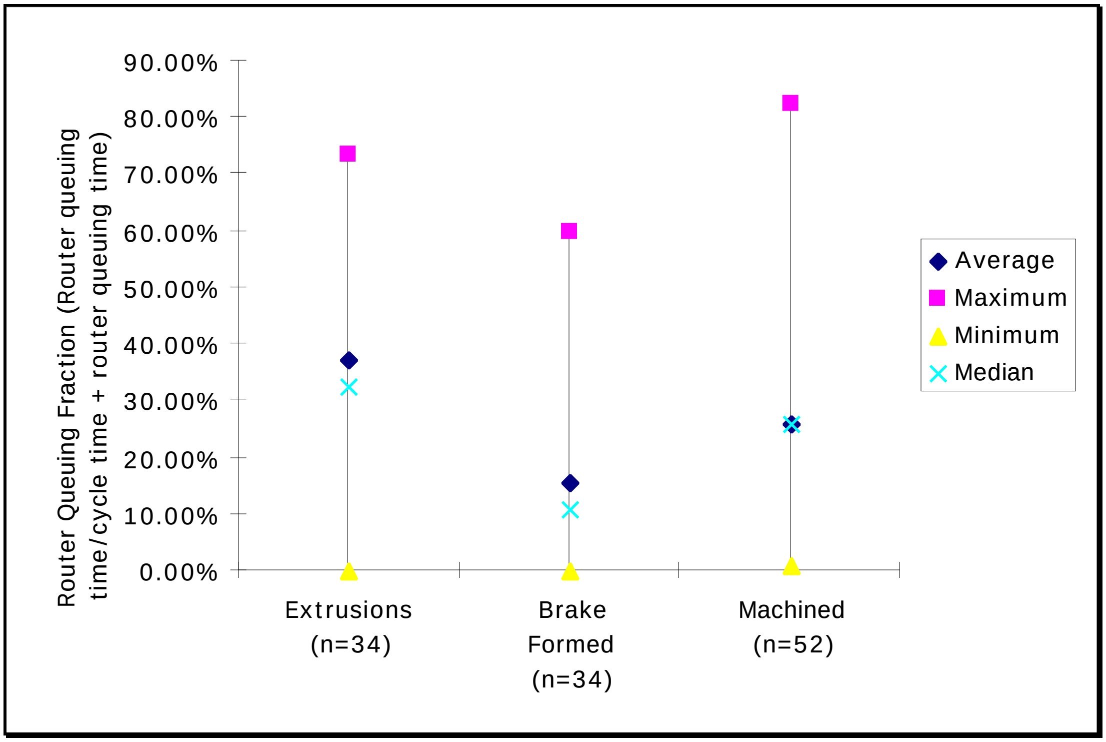

Figure 9: Router Queuing Time as a Fraction of Cycle Time for the Airframe Sector

3.3 Electronics Sector

The following plots (Figures 10-12) contain the usable raw data collected from the seven respondents from the electronic sector. They show the components of cycle time including waiting time and number of touch labor hours. As explained earlier this data reflects the history of a part in the work order rather than the entire work order. The length of the bar is the total cycle time (using work order cycle time as representative of part cycle time), which is the sum of the waiting time and the touch labor (on a per part basis). Appropriate exceptions to the data are noted with an asterisk.

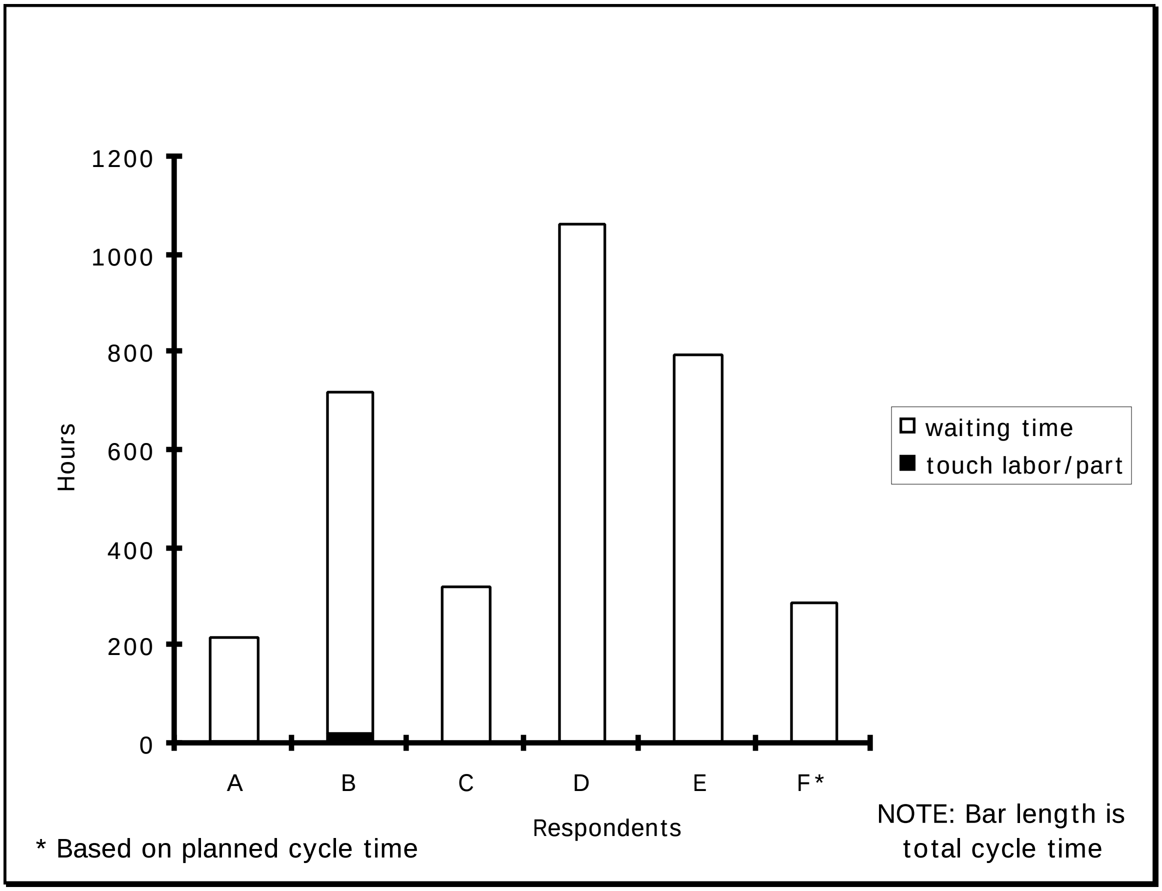

Figure 10: Electronic Sector - Printed Wiring Assembly

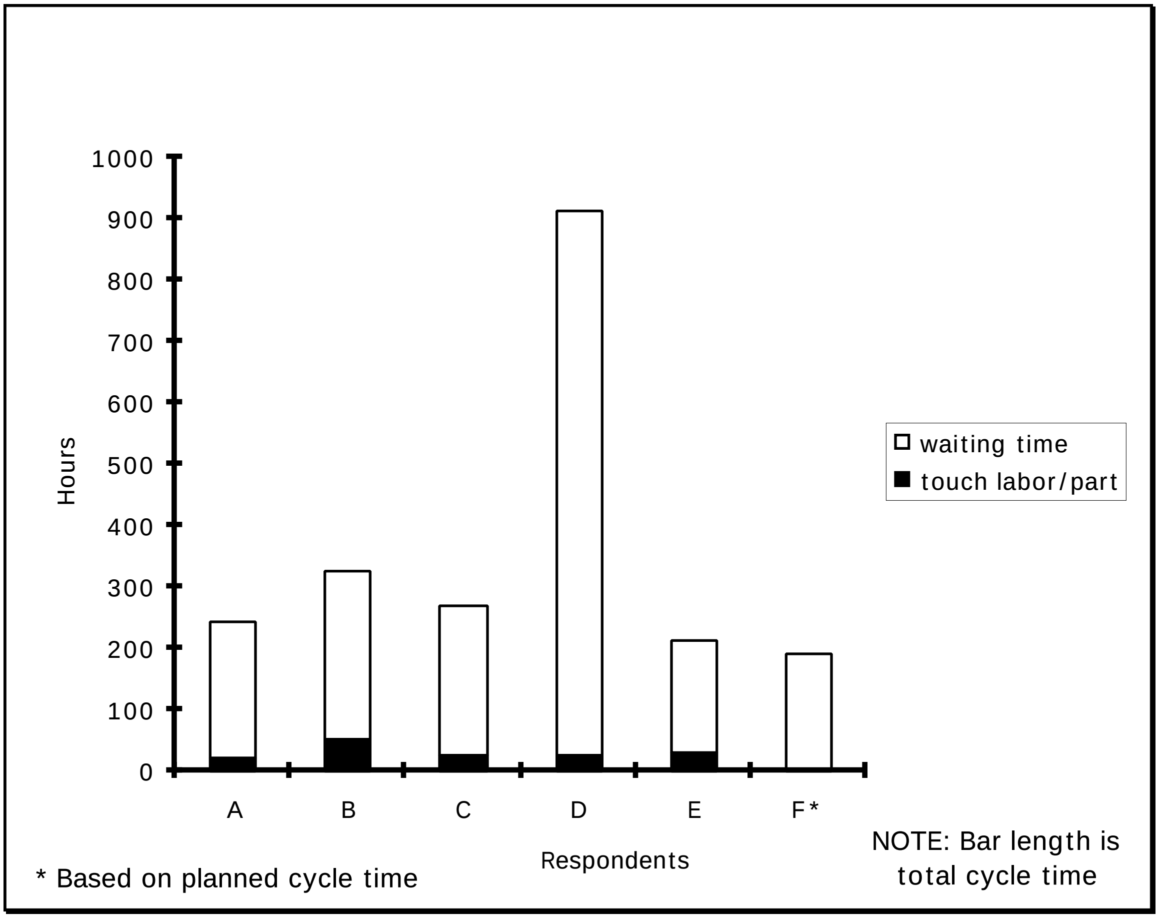

Figure 11: Electronic Sector - Chassis

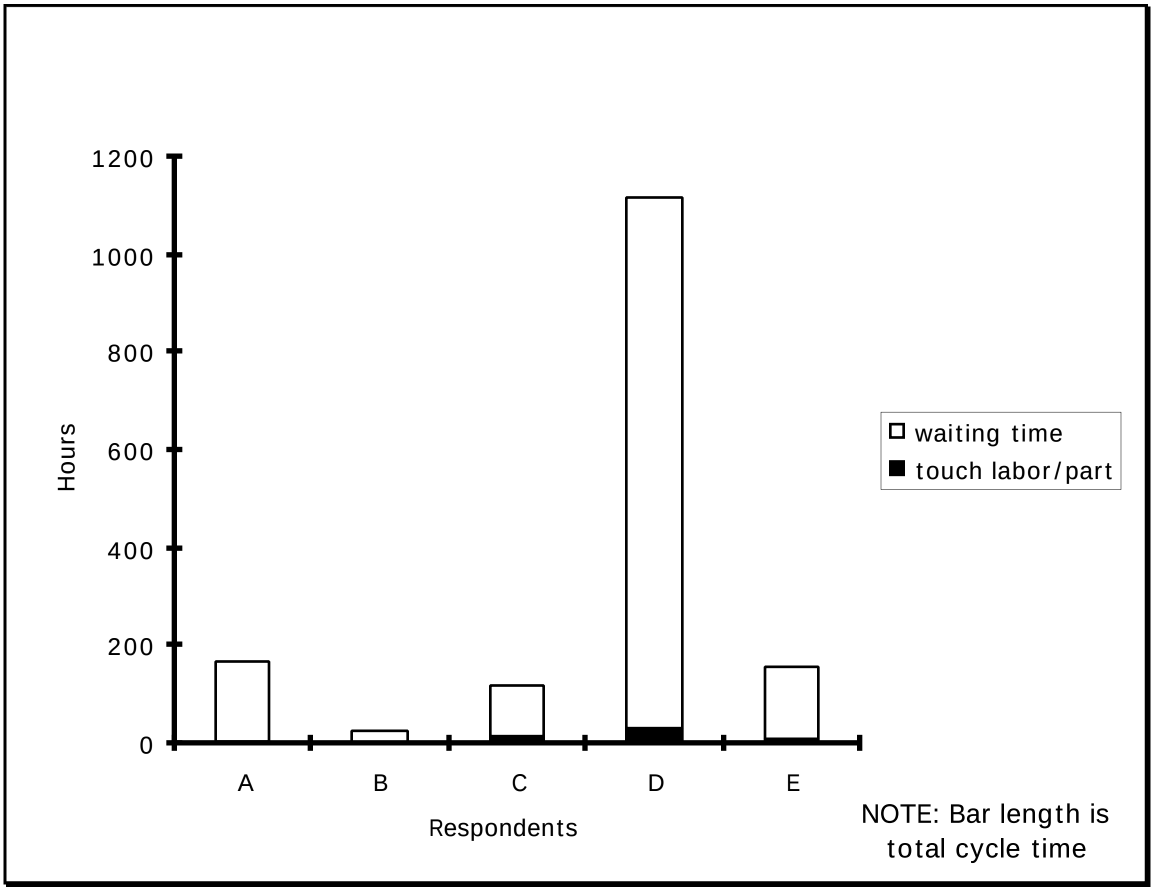

Figure 12: Electronic Sector - Cables/Harnesses

There were several other factors that were collected which provided additional information about the product flow. The first factor is the distance that the part travels as it goes through the fabrication or assembly process. The range of values for the distance traveled for the three parts benchmarked is displayed in Figure 13.

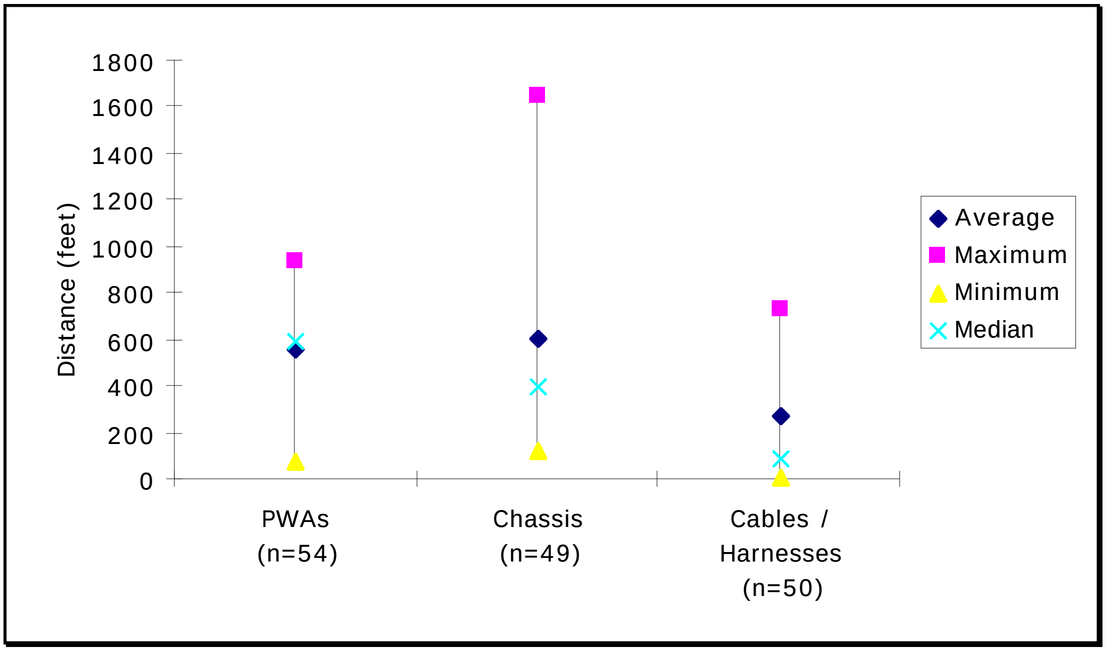

Figure 13: Distance Traveled by Parts Benchmarked in the Electronic Sector

We also collected information about the equipment reliability and worker training. This sector provided information about the time that the equipment or machinery that supports their products remained in working condition (uptime). This information is shown in Figure 14. We desired to collect information about the degree that workers receive skill training. We found that much of this information was estimated and was not verifiable but is reported in Figure 15.

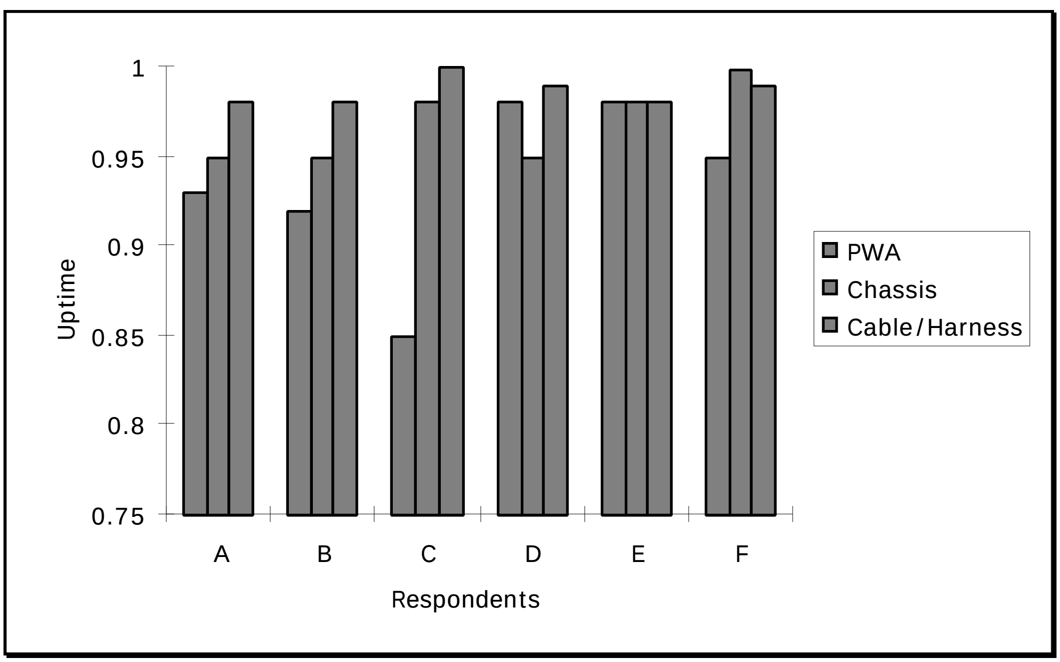

Figure 14: Equipment Uptime in the Electronic Sector

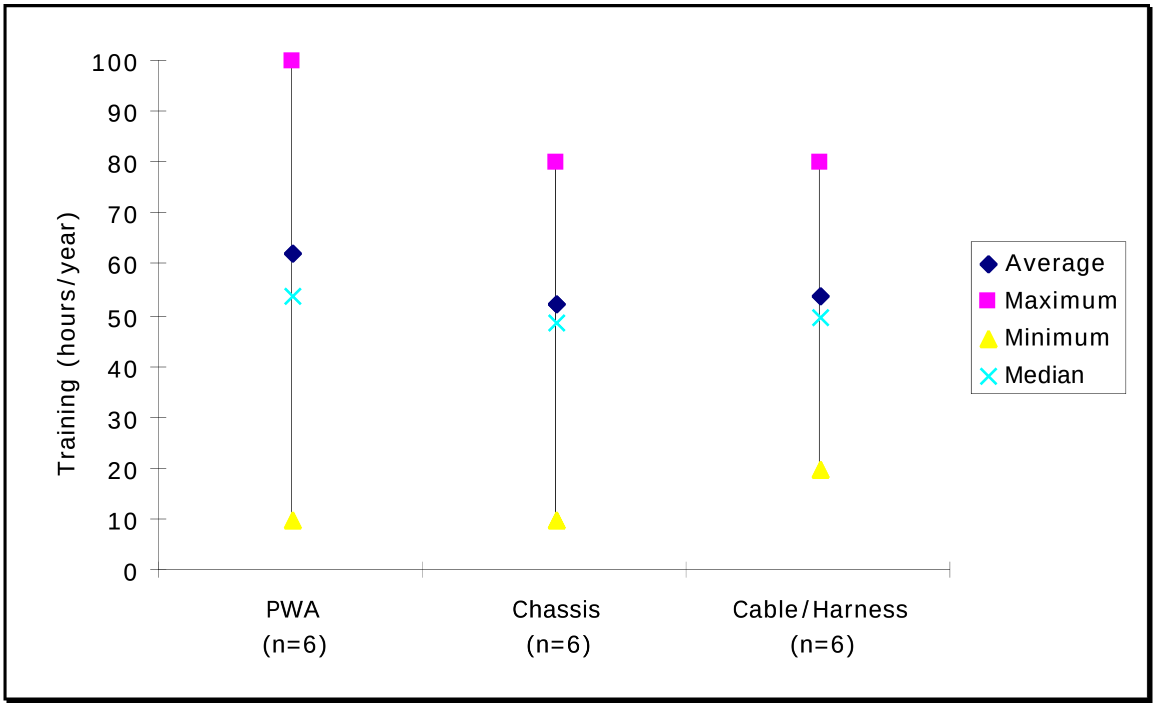

Figure 15: Worker Training in the Electronic Sector

Although we attempted to collect quality information in the questionnaire, the response was so varied that an analysis of the data was not feasible. Instead, some other information about quality was discerned from the questionnaire responses. We found that there were only a few government inspections required for the parts chosen by the respondents. In no case did government inspections exceed 3 mandatory inspections for a single part and the majority of the parts benchmarked required no government mandatory inspections. A consistent set of respondents answered the question about the percent of hours of rework conducted compared to actual touch labor hours with estimated data. This information is provided in Figure 16.

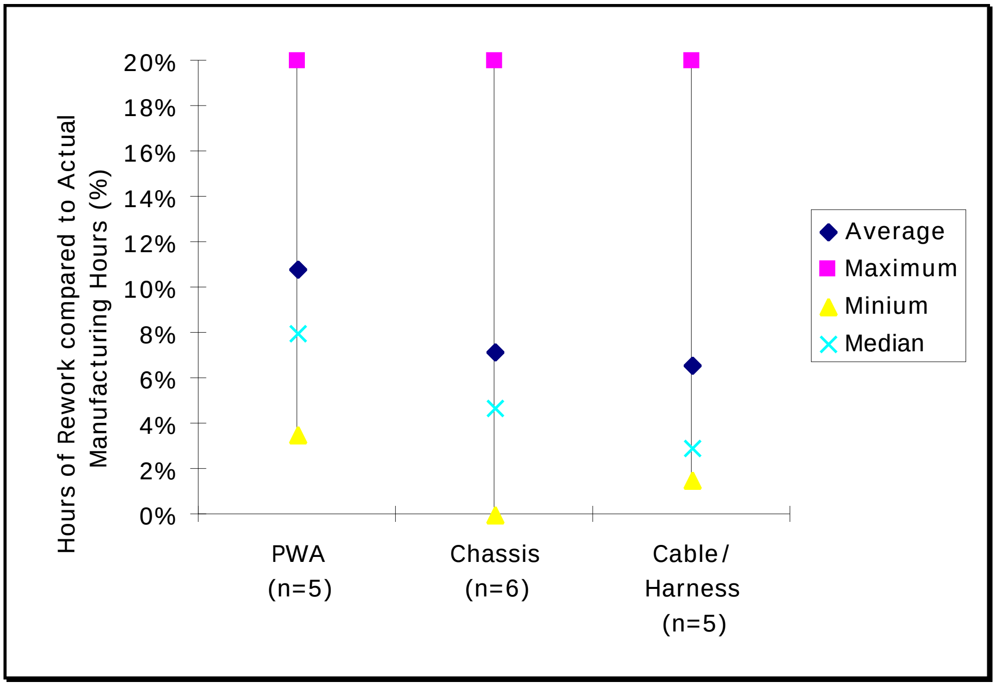

Figure 16: Rework Compared to Actual Manufacturing Time in the Electronic Sector

The extent of operator certification was captured in the questionnaire to see how extensive this idea had been adopted. We worded the question as the percentage of the manufacturing process that was inspected by operators. In the case of some respondents, the process inspections were done by automated means. If automated inspections were performed, the degree of operator inspection may be underrepresented. Although we observed operations in our data verification stage, we did not ascertain the degree of automated inspections. However, the results are presented in Figure 17.

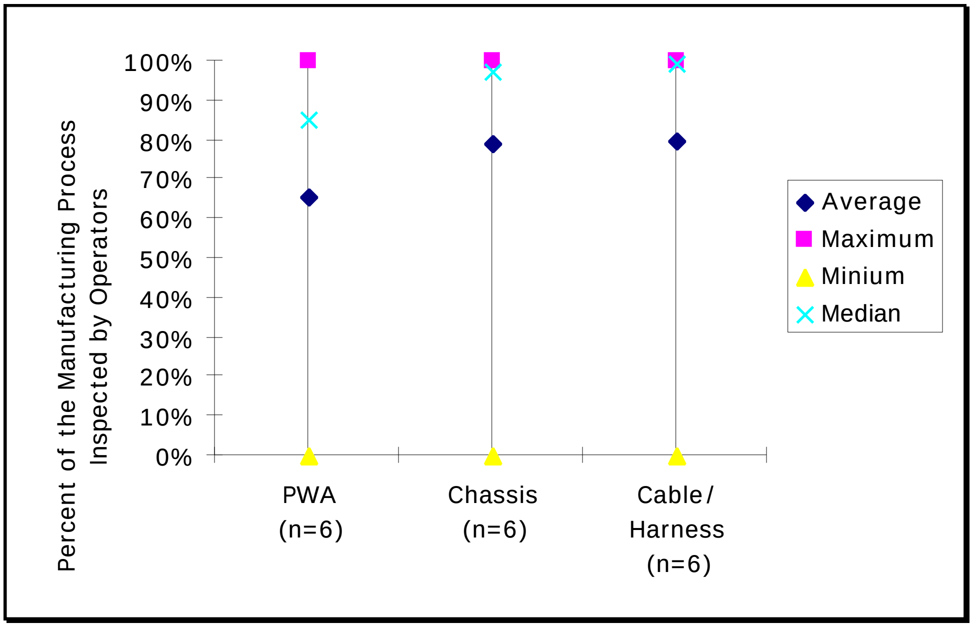

Figure 17: Operator Inspections in the Electronic Sector

The extent of employee involvement in process improvements is an important enabler of continuous improvement. We captured a series of information about this involvement in the questionnaire. In Figure 18, we present the percentage of submitted employee suggestions that were implemented in 1994. In Figure 19, we present the number of implemented suggestions per employee in the area for which our data was collected.

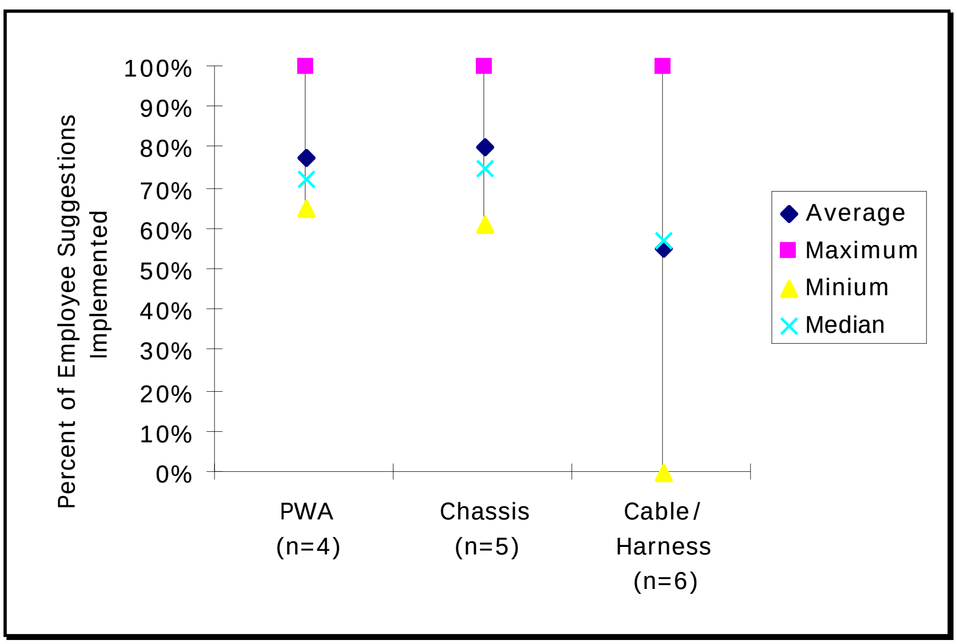

Figure 18: Submitted Employee Suggestions Implemented in the Electronic Sector

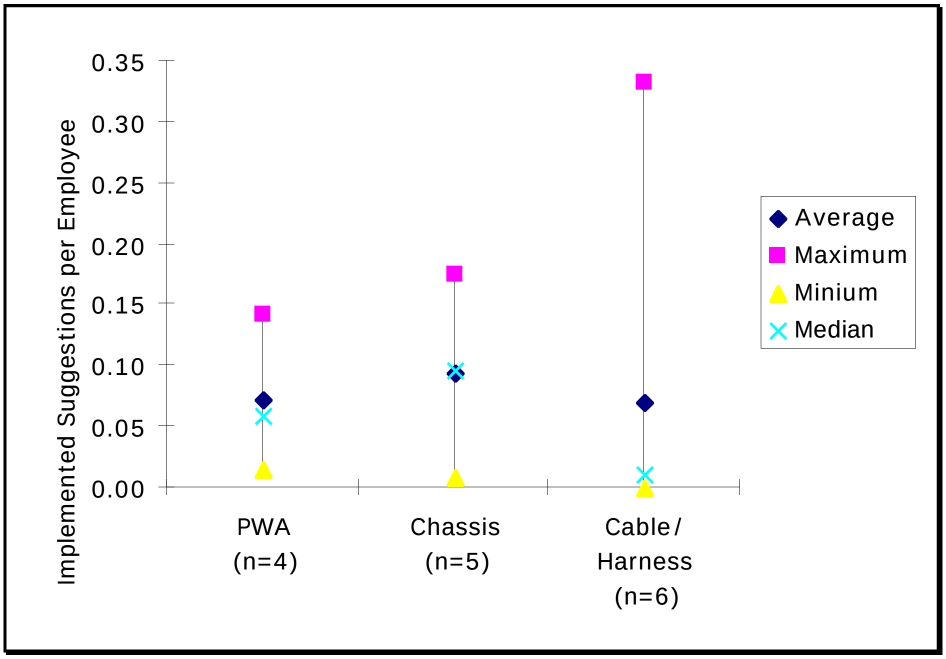

Figure 19: Implemented Suggestions per Employee in the Electronic Sector

3.4 Engine Sector

Although data was returned from each of the three companies in the engine sector, there was insufficient data on each specific parts benchmarked to present the data without highlighting a particular respondent. None of the three companies were able to provide complete data on all parts chosen for the study. Only data that fit the requirements as explained in previous sections were used for analysis. This reduction of information resulted in only 30 useful data points from two respondents in this sector. Therefore, the information is not displayed in raw form.

In other sections of the questionnaire, we were able to accumulate some information relative to the entire sector. Each respondent used cells for the manufacture of their turbine disks. In Table 2 below the number of unique part numbers in the cell and details about the cell process are shown. Similarly, details about the cell layout is provided in Table 3.

	Turbine Disk			Combustor		
	A	B	C	A	B	C
Number of Parts in Cell	10	1	7	22	1	113
Process Steps Mechanized	62%	0%	0%	0%	3%	0%
Process Steps using CNC	38%	39%	30%	0%	8%	0%
Process Steps with SPC	38%	0%	30%	7%	0%	0%

Table 2: Process Characteristics in the Engine Sector

	Turbine Disk			Combustor		
	A	B	C	A	B	C
Processing Equipment Space	33%	9%	95%	27%	91%	72%
Aisle Space	24%	1%	4%	31%	9%	22%
WIP Storage Space	1%	0%	1%	0%	0%	0%
Testing & Inspection Space	17%	2%	0%	5%	0%	6%
Rework / Repair Space	0%	0%	0%	27%	0%	0%
Other Space	25%	88%	0%	9%	0%	0%

Table 3: Facility Layout Characteristics in the Engine Sector

3.5 Summary

Many of the survey questions were not completed, either because the data was not available, or because there was a misunderstanding of the question. The most common difficulties with the surveys were the following:

- Industrial Engineering standard hour estimates were given rather than actual touch labor hours (in 50% of engine responses, 16% of electronics, 29% of airframe).
- Planned cycle time was given rather than actual cycle time (16% of engine responses, 16% of electronics, 29% of airframes).
- Companies could not provide the requested twelve lots of production data for electronics, twenty lots for engines, or three lots for airframes (66% of engine responses, 68% of electronics, 14% of airframe).
- In many cases the touch labor hours were greater than the cycle time (as explained earlier).
- In the airframe sector respondents reported difficulty in finding parts that were produced on three axis machines.
- Quality data was given in many forms, but not in defects per million opportunities, and not in defects per unit. Most companies reported that they did not collect

quality data on individual part numbers. The questionnaire requested information for shop quality history in the event individual parts numbers were not tracked but this was not provided in many cases. The responses for this inquiry were 38% of electronics responses reported d.p.m.o., 22% of electronics reported d.p.u., and 43% of airframes reported d.p.u..

- First pass yield percentage was often left blank (27% of electronics responses). Through verification phone calls, we discovered that many companies do not collect information on this metric, and other companies did not respond because of ambiguity in the metric itself ("first pass yield percentage" can refer to yield at final inspection, or yield at all inspections. Also in some cases the same part may fail an inspection twice, yielding a negative value.)
- Numerous other questions were left blank, or were marked "not available".

Several benefits arose out of the site visits. The researchers had a first hand look at both the product on which the data was based, as well as the process that created it. This experience and understanding proved invaluable later when the data was being analyzed, as some questions on the survey were too brief to capture information about the process. For example, one question asked how many of the machines for a given process were automated. More important in its affect on the cycle time was whether certain operations were automated rather than the total number of automated machines used in a process. Another important issue was whether automated operations, as valid fabrication time, was captured by touch labor measurements. For the sites visited, there was an operator for each machine whose time was charged for the work. This level of detail could not be captured on the survey (without greatly increasing the length and complexity of the survey).

Numerous other informative details were able to be captured by the site visits, such as the age of the operating machinery, which operations were charged to an "overhead" account and not included as direct labor hours, how the manpower for a given area was spread among the operations, and what made up the distance in the "Distance Traveled" (by the part) metric. As a numerical value, the "Distance Traveled" was not very informative in describing the layout of the process, but combined with the researcher's experience in walking the path flow and seeing what comprised the total distance, a valid set of data was obtained. In most cases where the data was incomplete, the verification trips were able to collect all the data needed for analysis. Furthermore, in a few cases, newer data was substituted for old incomplete data.

The largest problem encountered in verifying the data on the surveys was that in many cases (38% of the electronics sector, 29% of the airframes sector) the parts on which the surveys were based were no longer in production. In these cases, it was not possible to see the process flow, or the process layout. There were also two cases where the individual who had completed the survey was no longer with the company. In these cases it was difficult to reconstruct the data given, or obtain the new data that was needed.

During the course of this benchmarking effort we saw very few respondents that tracked their actual cycle times. Even if the data was available to the respondents, actual cycle time was not considered an important metric to track and trend over time. Many organizations depended upon planned lead times or MRP derived span times to estimate their cycle times. We found that this estimation process underestimated the actual cycle times experienced.

4. Analysis

4.1 Flow Efficiency

From the Lean Aircraft Initiative research there are a number of enablers to leanness. Flow optimization is just one of those enablers. Some measurement of the flow efficiency is proposed as a metric for comparing different factory operations. If sufficient information can be gathered using this metric to characterize gross performance then relationships to lean practices may be able to be established.

One of the objectives from this benchmarking effort was to gain an understanding of the efficiency of the production system. As you will remember, the more efficient production systems would have production cycle times to build their products only slightly more than the sum of the individual part processing times. Therefore, we can define a term we call flow efficiency as:

$$\text{Flow Efficiency} = \frac{\text{Fabrication Time}}{\text{Cycle Time}} \qquad \textbf{Equation 1}$$

Although it is desirable to obtain individual part fabrication times, each sector did not gather this data on a day to day basis. Therefore, a surrogate flow efficiency definition was devised that used information that was available from each sector. This flow efficiency definition depends on labor touch time accumulated on each part as a surrogate for fabrication time. Choosing this measure is accurate if touch labor time is accumulated during the entire time the part is being fabricated. There are times that no touch time may be accumulated because the part fabrication is occurring by some automated processing such as a numerically controlled machining operation. In our observations during our data verification visits, we did not witness nor did specific data requested indicate that a single worker was operating multiple machines or conducting multiple operations. We observed workers associated with each operation whether it was manual or automatic.

This method of calculating fabrication time overrepresents the amount of time accumulated for all activities relative to the part fabrication whether it was due to fabrication or ancillary activities. For instance, the way this data was collected time devoted to performing setup operations would be captured. Therefore, the data probably represents a conservative representation of the amount of non fabrication time (wait time). With these caveats explained about using the actual labor hours, here is a surrogate method of explaining flow efficiency:

$$\text{Flow Efficiency} \quad \frac{\text{Actual Labor Hours}}{\text{Cycle Time}} \qquad \textbf{Equation 2}$$

Because of the lot size ambiguity explained earlier the only method to obtain a common definition of flow efficiency was to base the fabrication time on a per part basis. Since the parts stayed in the factory for the entire time the lot was in the factory the cycle time of the part is the same as the cycle time of the work order. By using the formula in Equation 3 there is a common definition of flow efficiency that can be applied to all sectors.

$$\text{Flow Efficiency} \quad \frac{\text{Actual Labor Hours per part}}{\text{Total Cycle Time the part is in the system}} \qquad \textbf{Equation 3}$$

Actual labor hours per part can also be compounded by the number of people in the crew. We did not find instances of multiple crew members but this could be a factor. Therefore, the following formula was determined to accurately capture the idea of flow efficiency in fabricating a part:

$$\text{Flow Efficiency} \quad \frac{\text{Actual Labor Hours per part per crew member}}{\text{Total Cycle Time the part is in the system}} \qquad \textbf{Equation 4}$$

The major elements of the data collection effort centered on the time it takes to process a part compared to the time the part was in the system. The data was not available for individual parts. Instead, data in the factory was collected on work orders which could have one or more parts (lot size). Therefore, the principal data elements collected were actual labor hours to fabricate a lot size of parts and actual time the work order was in the system from release of the work order until the work order was closed out. To characterize the total time the part was in the system (cycle time), it can be subdivided into three constituents: time from the release of the work order until first operation performed, total time used to fabricate the work order, and total time the work order was waiting to be fabricated. This concept is best illustrated in Figure 1. The airframe sector collected data on all three categories. In the electronic and the engine sectors, information was only gathered on the time from first operation until the close out of the work order. Therefore, the flow efficiency calculation that is the most common between the three sectors is given by the following formula:

$$\text{Flow Efficiency} \quad \frac{\text{Actual Labor Hours per part per crew member}}{\text{Total Cycle Time the part is in the system - router queuing}}$$

Equation 5

During our data verification effort, we were able to discern that the crew size was one in all cases that we could observe or for which we could question respondents. Equation 5 became the basis for all calculations of flow efficiencies and correlation analyses that follow. Figures 20 and 21 show the results of this flow efficiency calculation for the airframe and electronic sector respectively.

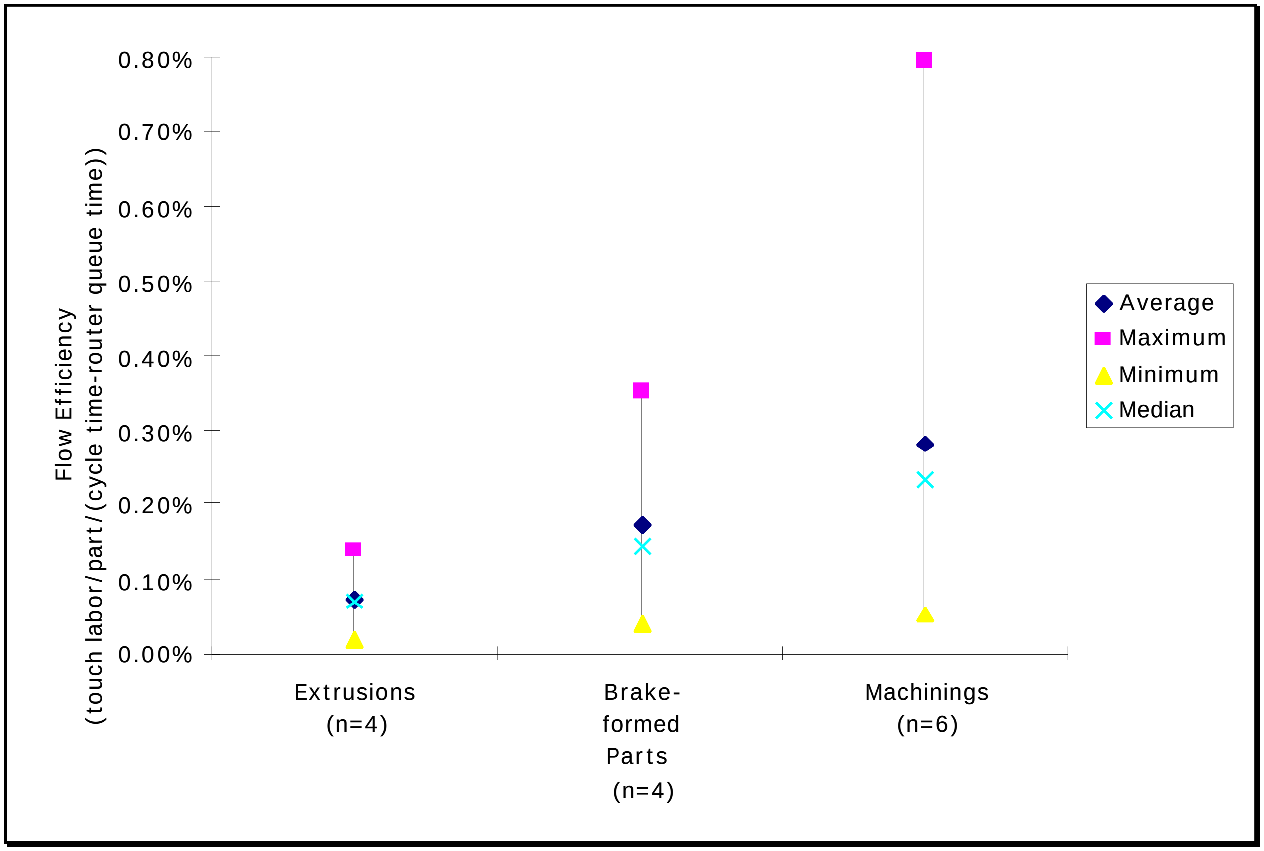

Figure 20: Airframe Sector - Flow Efficiency (Router Queue Removed)

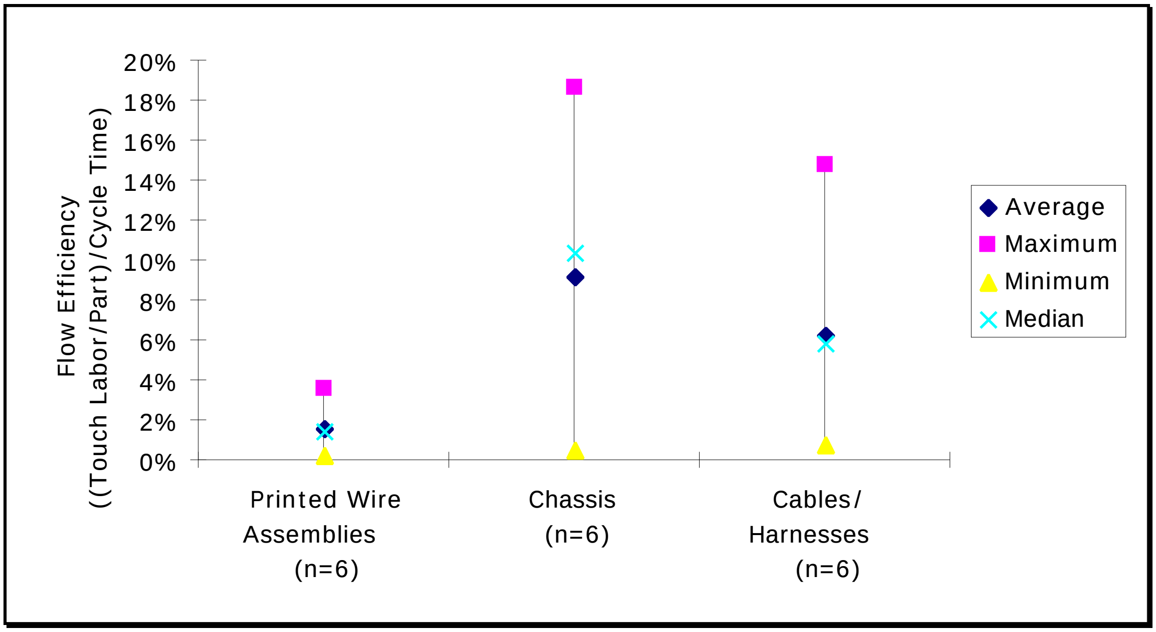

Figure 21: Electronic Sector - Flow Efficiency

4.2 Hypotheses

We had hypothesized that there would be higher flow efficiencies with lower lot sizes, higher flow efficiencies with shorter distance traveled and higher flow efficiencies with fewer process steps. We looked at the data to see if these hypotheses were supported by the data.

Our initial analysis focused on each sector and we saw confusing results. It was thought that each sector represented only a small portion of the total data so we combined the data from all sectors. It was at this point that we established the common definition of flow efficiency (Equation 5). With all sectors combined, the data revealed more information.

We also noticed that the type of process in which the factory was involved was highly related to the flow efficiency. We grouped our respondents into two categories, job shop processes and flow shops/dedicated lines. A job shop process is a process in which the layout of the factory is dictated by the type of machine or operation. Therefore, in a job shop process the part travels to the area in which the specific operation required can be performed. This often results in a “spider web” part flow path as the part is processed through each operation required to fabricate the part. In a job shop, a similar part does not necessarily travel the same flow path each time. A flow shop is a factory layout that has been devised so that process operations are nearly contiguous to one another and there is a consistent path that the parts take as they move through the factory operation. A dedicated line is the fully contiguous set of operations dedicated to the production of this part (or part family).

4.2.1 Correlation Analyses

We performed three correlation analyses to test our hypotheses: flow efficiency versus lot size, flow efficiency versus distance traveled and flow efficiency versus number of process steps. We then performed a multivariate analysis to test the strength of the interrelationships. These analyses follow:

4.2.1.1 Flow Efficiency vs. Lot Size.

In the case of lot size correlation we were able to define a theoretical maximum flow efficiency we would expect to observe based on the lot size of the work order. The explanation for theoretical maximum comes from the flow efficiency equation as well as a practical example.

If we take the situation in which the fabrication time for the part is the same as the cycle time for producing the part (in other words the best possible outcome), then we can demonstrate the effect of lot size. From the flow efficiency Equations 2 through 5, we can see that if the fabrication time is equal to the cycle time that the result for flow efficiency is the reciprocal of the lot size. Therefore, if the lot size is 10 then the theoretical maximum flow efficiency that would be expected for this lot size production is 1/10 or 10 percent. Therefore, for a given lot size, if only one part is processed at a time, while the rest of the parts wait (either before the station, unprocessed, or after the station, waiting to be moved to the next station), the theoretical maximum flow efficiency is the reciprocal of the lot size. Thus 100 percent flow efficiency is possible only for a lot size of one.

Another way to depict this limiting factor of lot size to flow efficiency is depicted in Figure 22 where the lot consists of three parts and there are three processes to make this part. In this depiction, there is no time scheduled between operations; therefore, the only waiting time is the time waiting for the other pieces to complete the current operation. At each process, and also in total, each piece has to wait two units of time for each unit of time it is being processed. Therefore, each piece accumulates three units of fabrication time over the three processes and the cycle time is nine units of time. This results in a maximum flow efficiency of 1/3 which is the reciprocal of the lot size. If there is any additional wait time before any process operation then the flow efficiency will then be less than the reciprocal of the lot size.

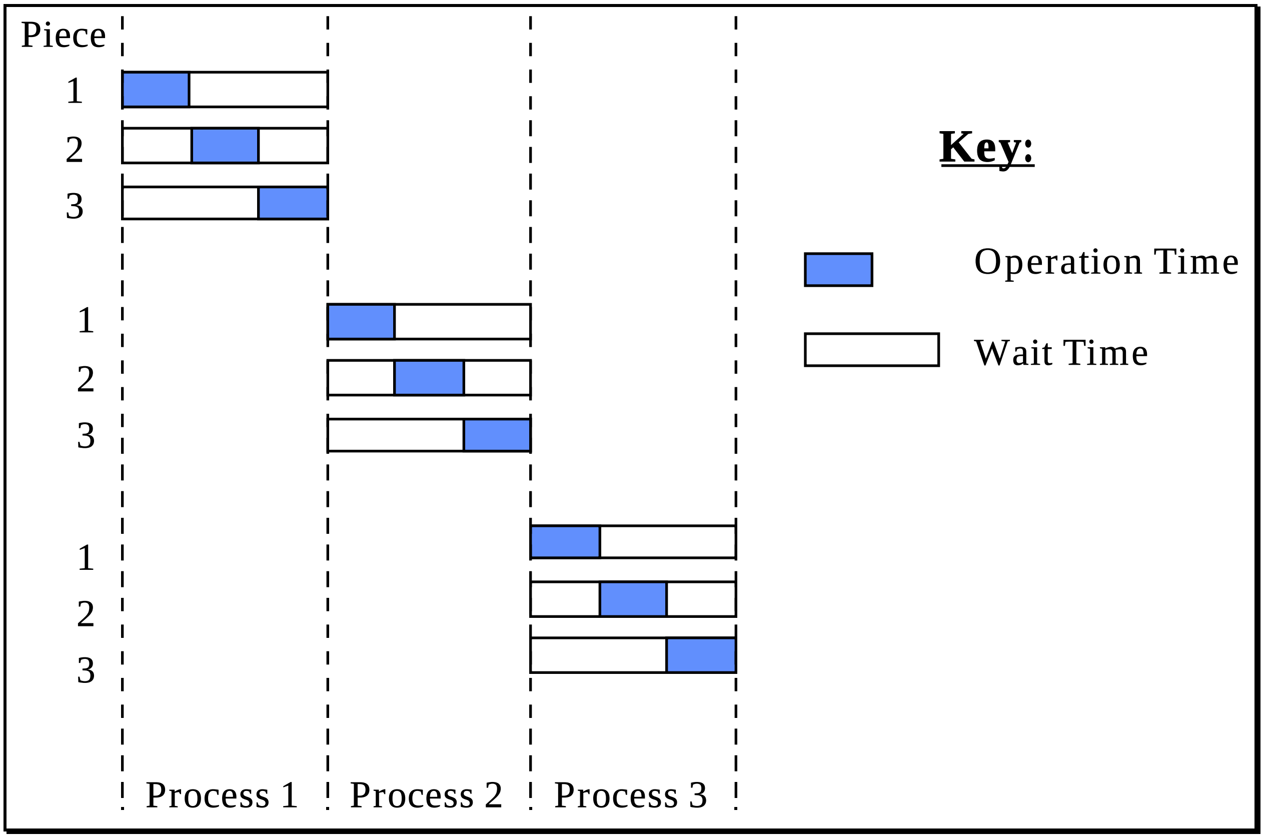

Figure 22: Effect of Lot Size on Flow Efficiency

In Figure 23, we display the entire set of useful data from the benchmarking effort in a plot of the flow efficiency versus lot size overlaid with a plot of the curve representing the theoretical maximum flow efficiency.

The graph shows that most companies lie well below the theoretical curve. Those that lie above the curve represent difficulties in the data. These difficulties are associated with lot size ambiguity explained earlier. Some companies document groups of parts as the work order quantity (which may be a function of the quantity ordered by the customer) but process parts in a different "batch size." Thus the work order may represent 30 units but parts are actually processed in lots of 5.

Before the data verification effort there were many more points that were above the theoretical curve. The data verification effort corrected many of the problems. The remaining data points were not resolved although the data is deemed accurate relative to the ordinate.

In those cases where it was possible, the researcher tried to discover the processing lot size, which would then shift the point along the X-axis to the left to correspond to this lot size. However in many cases the lot size fluctuated throughout the process, or the processing lot size could not be determined.

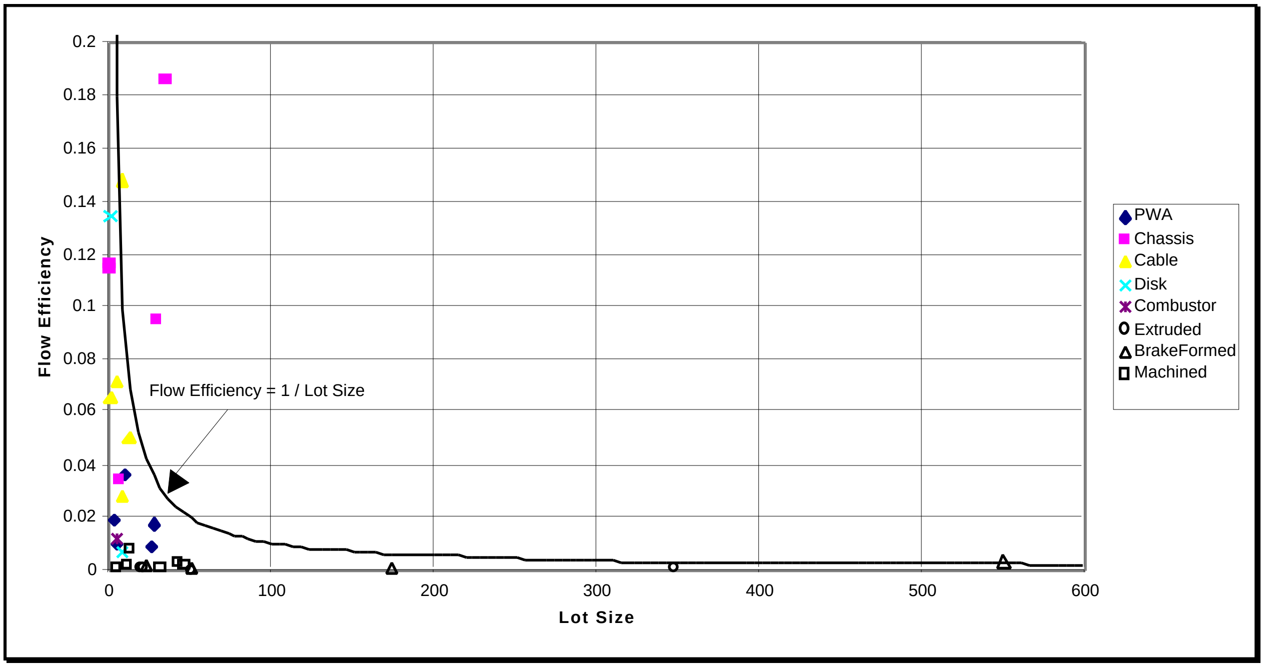

Figure 23: Flow Efficiency versus Lot Size

For a given choice of lot size the flow efficiency possible is limited by this lot size decision. Therefore, the only possible improvement in efficiency is the vertical distance from the data point to the reciprocal of the lot size line. A choice of a high lot number size drastically limits the flow efficiency that can be obtained. This effect can be seen in Figure 24.

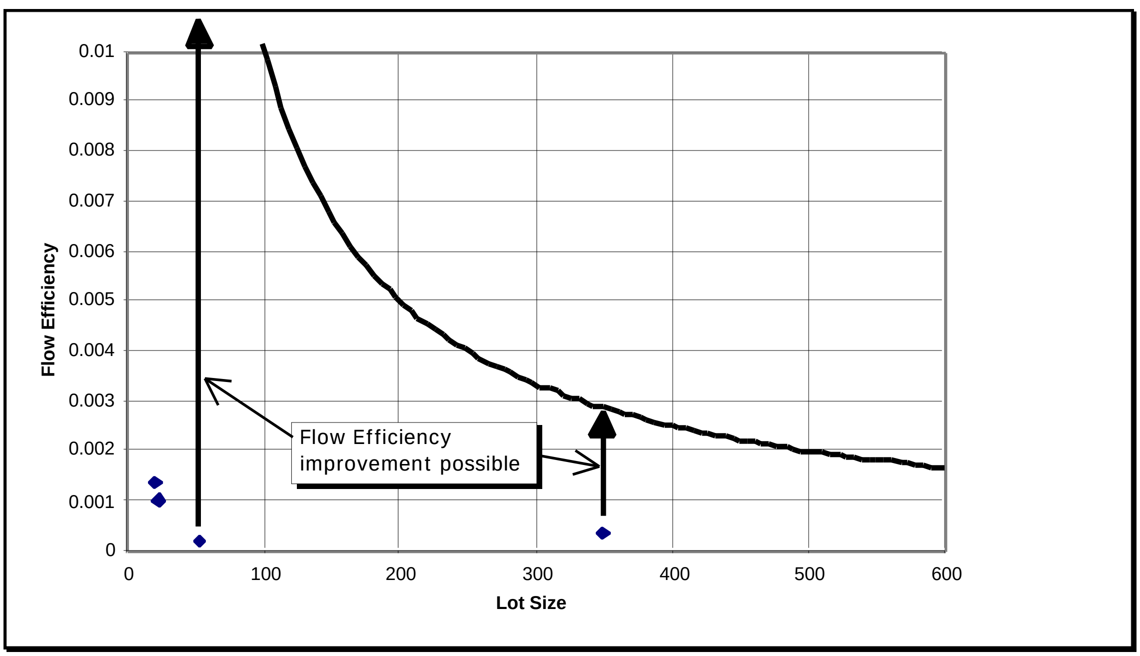

Figure 24: Flow Efficiency Improvement Relative to Lot Size

4.2.1.2 Flow Efficiency vs. Distance Traveled

It was hypothesized that those parts that had a shorter travel distance would have a higher flow efficiency. Figure 25 is the correlation plot of flow efficiency to distance traveled. This plot is an effort to discover if there is any correlation between the distance traveled by a part in a given process and the flow efficiency. Since the cycle time consists of processing time (direct Touch Labor hours), plus waiting time (either waiting for a part of the lot to be processed, being transported between operation steps, or waiting for other lots to be processed (due to scheduling problems), it is reasoned that a part that travels further will incur more cycle time without incurring touch labor resulting in lower flow efficiency. As can be seen in Figure 25, there is a rather drastic reduction in flow efficiencies when the distance the part travels is greater than 2000 feet.

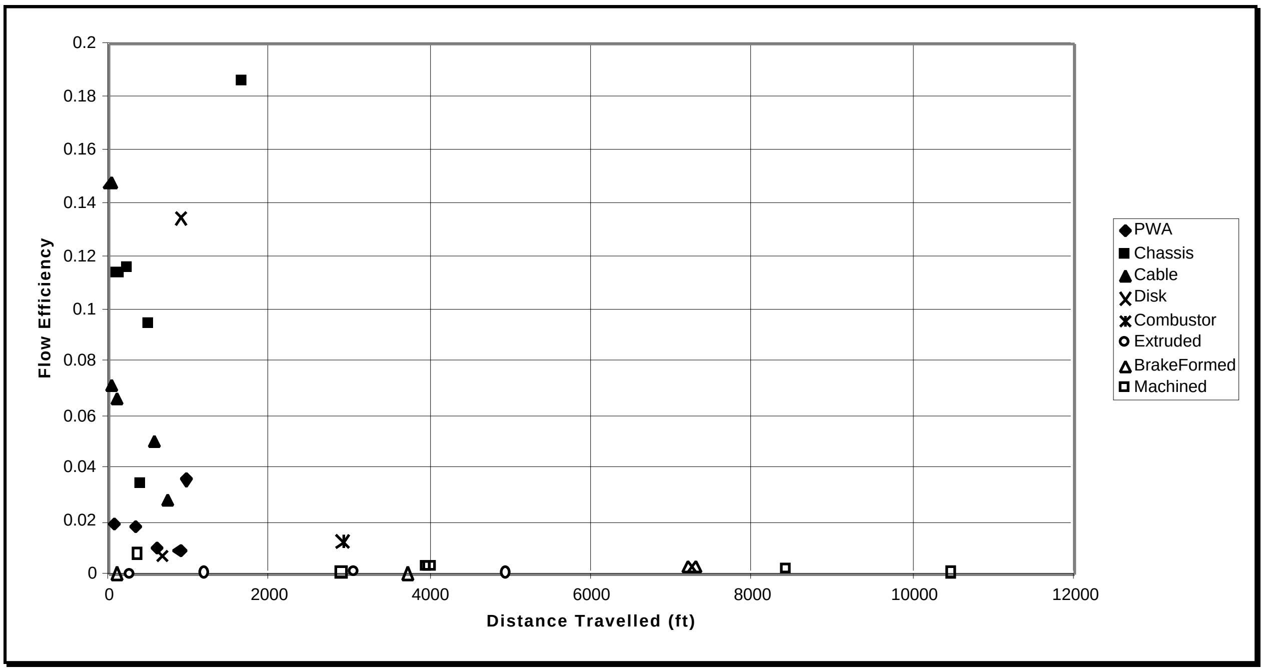

Figure 25: Flow Efficiency versus Distance Traveled

4.2.1.3 Flow Efficiency vs. Process Steps

The plot in Figure 26 is a test to see if the complexity of a part fabrication (as is measured by the number of process steps) is correlated with the flow efficiency. We determined the number of process steps using the work instructions and counting the number of steps listed. We found that there were differences in the complexity of the steps between work instructions. Since the size of a process step is arbitrary, two companies could follow exactly the same procedure to make a part, with one reporting 20 process steps and the other 35. Therefore, there was significant variation in process steps independent of process characteristics between the respondents. Because of this, we think that this correlation is inconclusive. The graph in Figure 26 supports this contention because of the large scatter of data particularly in the 0 - 30 process step range.

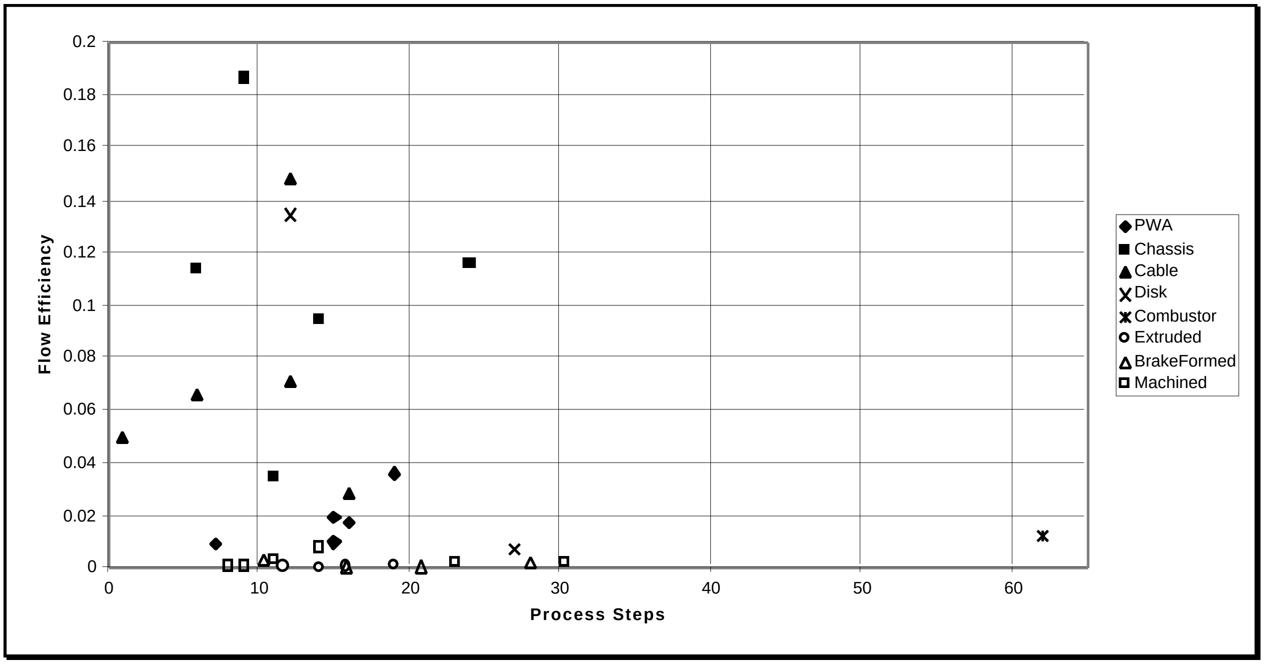

Figure 26: Flow Efficiency versus Process Steps

4.2.1.4 Multivariate Analysis

Using all the useful data, a multivariate analysis was performed to see if there were multiple relationships. In this analysis, the outcome was flow efficiency and the input variables were lot size, distance traveled and number of process steps. A best fit linear model using the inverse function of the above input variables was used for this analysis. The result was the equation below:

$$\text{Flow Efficiency} = \underset{(.58)}{1.7\left(\frac{1}{\text{Distance Traveled}}\right)} + \underset{(.024)}{0.093\left(\frac{1}{\text{Lot Size}}\right)} \qquad \textbf{Equation 6}$$

The analysis indicated statistical significant relationships between distance traveled and lot size (standard deviation noted under each term); however, there was no significant relationship with process steps. This equation yielded an adjusted r^2 value of .43 which means that the equation explains about 43 percent of the variance in the flow efficiency.

4.2.2 Process Type

Using the two differentiations of process type explained earlier, job shop and flow shop / dedicated line, we are able to show definite grouping of the data. Figure 27 represents this grouping. Job shops tend to have larger lot sizes. As we have seen, this naturally reduces the flow efficiency. What is striking however, is the large variation in flow efficiency in the flow shop or dedicated line process type. From Figure 27, the flow efficiencies of flow shops or dedicated lines range from values associated with job shops (less than one percent) to as high as 18 percent. This difference sparks some specific analyses of wait times relative to this process type later in this report.

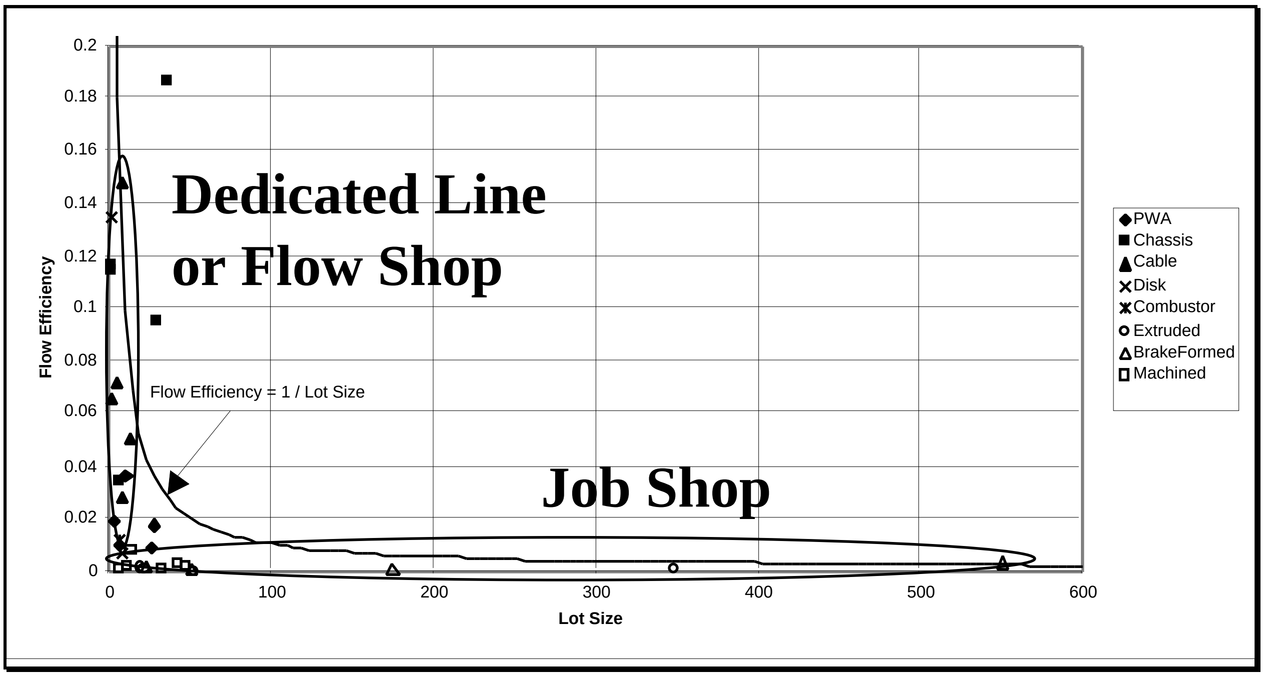

Figure 27: Flow Efficiency and Process Type

There are other factors that influence the performance of job shops other than flow efficiency. Some of these factors are associated with what the facility has optimized. For instance, the facility could be optimizing the utilization of its machinery or the use of available machine operators. This could have impact on the lot size decision. As we know, this can cause great impact on the flow efficiency. The facility could be capacity limited or be processing few parts for which data was collected. Therefore, the production environment when data was collected could have affected the data. For instance, the parts chosen could have been expedited through the factory or other parts could have had higher priority causing the parts chosen to experience variable cycle times.

However, in flow shops or dedicated lines, there are few of these other considerations. If there is a delay in the product, once introduced into the factory, then its delay is due to some inefficiency in the flow or line. Because there are less complicating factors with flow shops or dedicated lines it is easier to make some conclusions about wait time.

4.3 Wait Time

In viewing the raw data in Figures 4-6 and 10-12, it is apparent that the major portion of the cycle time to produce parts is associated with waiting. We analyzed this wait time to obtain some information about the components of wait time. We chose to categorize wait time into three components: transportation delay, lot processing delay and storage delay. There are other categories of wait time that could be defined but our data was not sufficiently detailed to provide any finer information than these three categories.

Since the electronic sector data was obtained on a per part basis, much of the information about wait time had to be approached differently than in the airframe sector. In the airframe sector, the wait time for a work order was the difference between the cycle time and the touch labor time accumulated on the work order. In the electronic sector this was not the case because of the lot size ambiguity explained earlier. Therefore, the approach in the electronic sector analysis was different. As before, the limited results from the engine sector prevent display of this information on a sector basis.

We also analyzed the wait times relative to type of process used in the operation. Most of the electronic sector and engine sector data was from flow shops or dedicated lines while much (but not all) of the responses from the airframe sector were from job shops. As before the analysis of the data by process type provides some different information.

4.3.1 Airframe Sector

The fraction of the cycle time that is due to wait time is calculated for the airframe sector and is presented in Figure 28. Most of the cycle time to produce the part is involved in waiting. There are three components of wait time; lot processing delay, transportation delay and storage delay.

It was possible to distinguish the lot processing delay in the airframe sector. Since the lot processing delay is a function of the lot size, the expected lot processing delay is simply the individual part processing time multiplied by one less than the lot size. This calculation was made for each of the parts benchmarked and was less than 3 percent of the total wait time (see Figure 28). In this sector, there was no data to differentiate between storage delay and transportation delay so these two categories are combined. Informal discussions with those respondents visited during the data verification effort indicated that transportation delay was not the major component of wait time.

	Wait Fraction	Lot Processing Delay
Extrusion	95%	2%
Brake Formed	97%	2%
Machining	94%	3%

Figure 28: Airframe Sector Wait Fraction and Lot Processing Delay

4.3.2 Electronic Sector

Because of the lot size ambiguity a different analysis approach in this sector was necessary. Since the actual values of wait time could not be determined in this sector, a method to bound the wait times was developed. First, a maximum value of wait time was determined using Industrial Engineering (I. E.) standard hours for the estimated time for producing a part. In this calculation, the assumption is that the I. E. hours are the minimum value for time devoted to working on the part, therefore, the remaining part of the cycle time would be the maximum value for waiting time. This assumption was tested during the data verification effort. Respondents stated that their I. E. hours were less than their actual hours to produce the parts. Therefore, we are confident that we are calculating the upper bound on wait time fractions. This assertion was wrong in only one instance: the chassis for company B. In this case, the actual time to produce the product was less than the I.E. standard hours and the values for company B became negative. We chose not to display the results for company B chassis in Figures 30 and 33 because the common assumption for comparison was not true and we could not determine why there was a difference. In all other instances, Figures 29 through 31 represent the maximum wait time fraction for the respondents. It is interesting to note that in each part there is at least one respondent that is significantly better than other respondents.

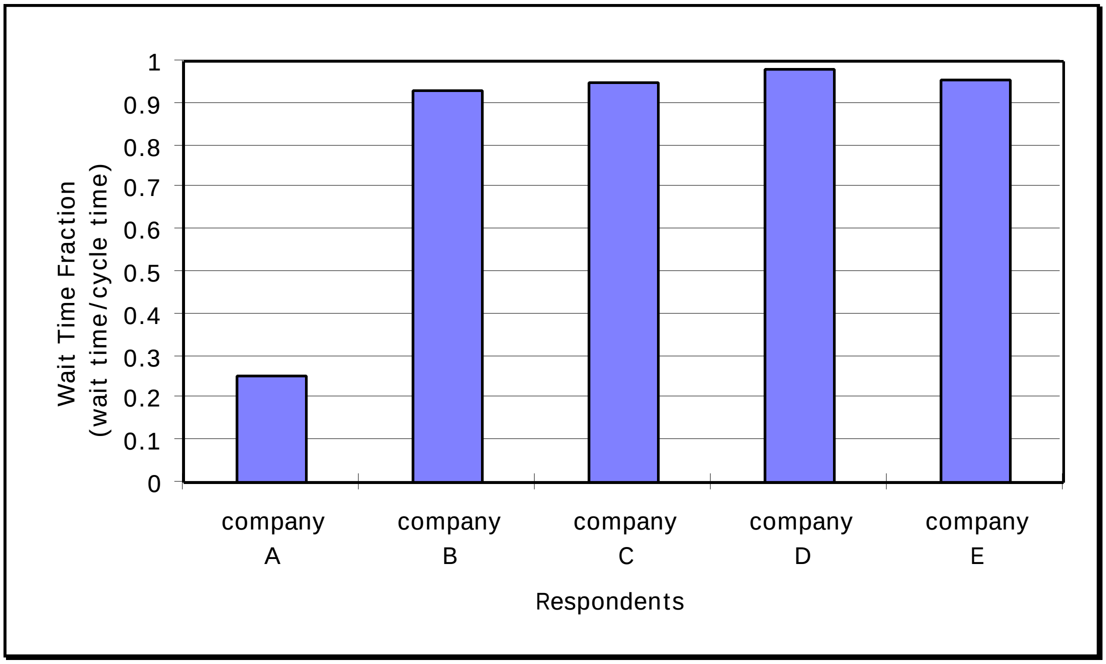

Figure 29: Electronic Sector Maximum Wait Fraction - Printed Wiring Assembly

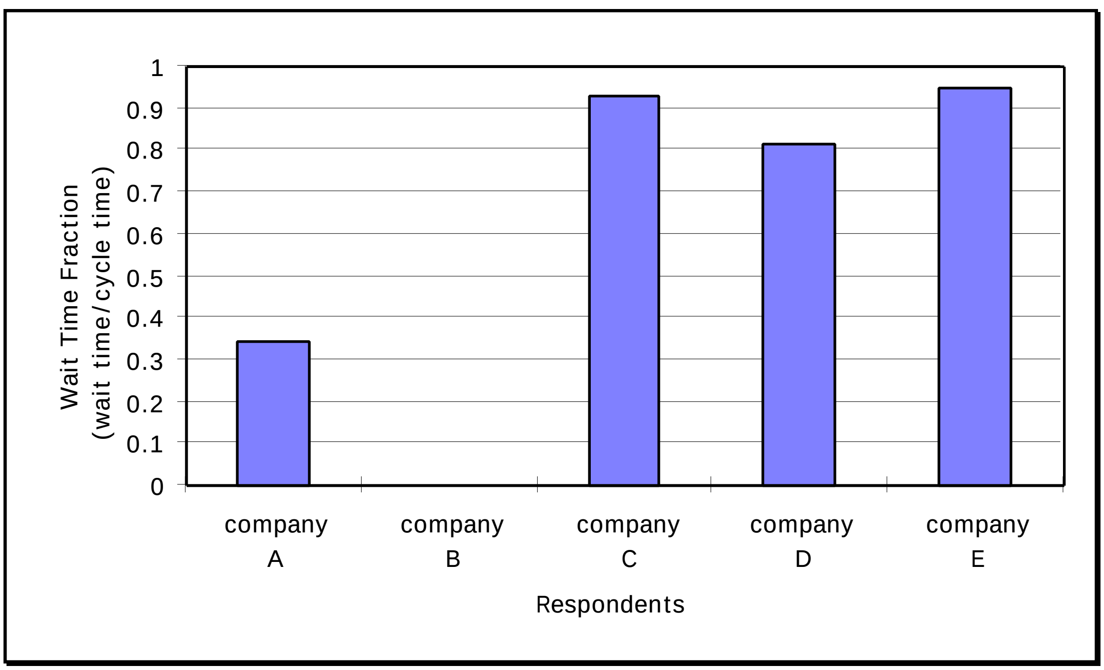

Figure 30: Electronic Sector Maximum Wait Fraction - Chassis

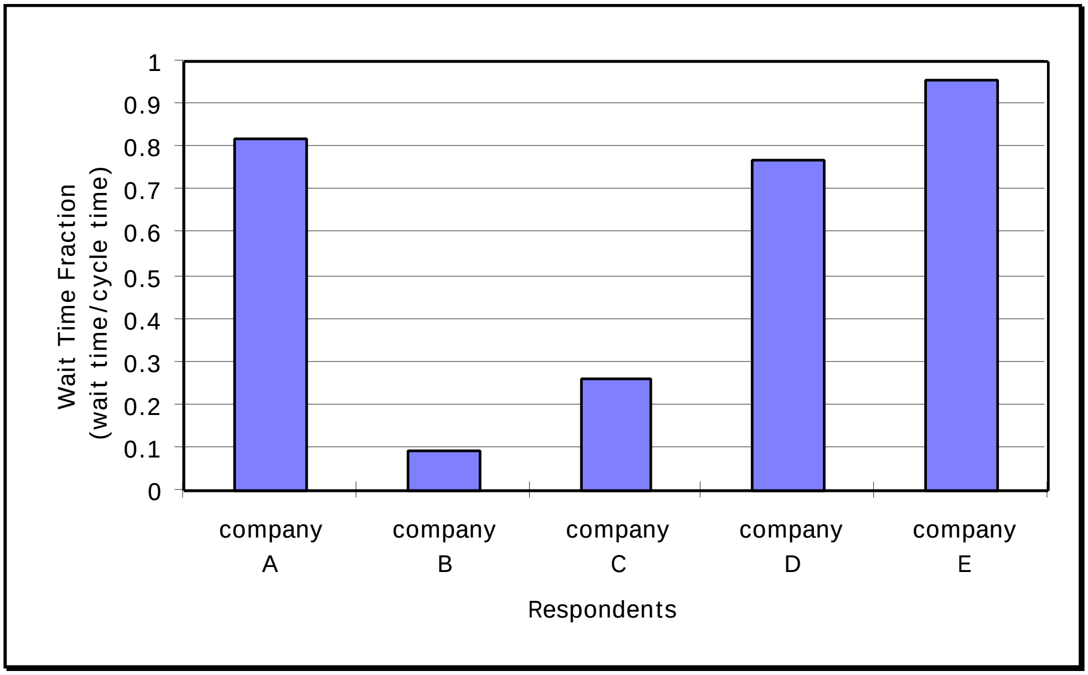

Figure 31: Electronic Sector Maximum Wait Fraction - Cable/Harness

In order to demonstrate the lower bound to the wait fraction we again used the I. E. standard hours to show what level of realization[2] would be necessary to have a situation in which there was no wait time. This measure would be useful to respondents who know there historical realization factor. By comparing the realization factor necessary to produce zero wait time and their actual realization factor a respondent may be able to estimate their wait times. Figures 32 through 34 show this data. In interpreting these figures a low value is better.

[2] Realization or realization factor is the value times the I. E. hours necessary to equal the actual hours to accomplish a task.

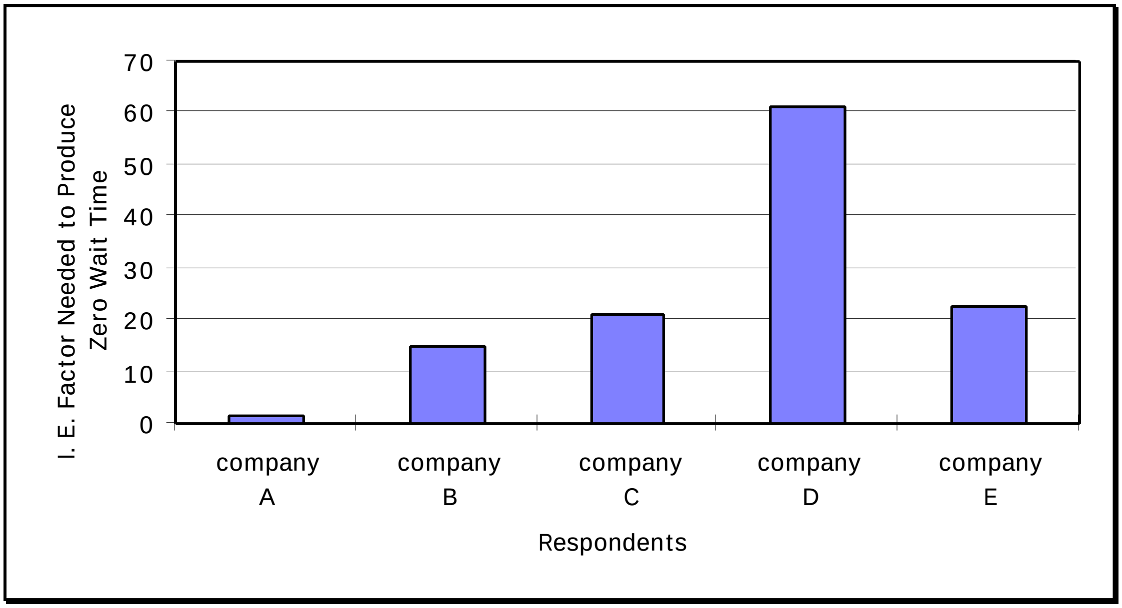

Figure 32: Electronic Sector Realization Factor for Zero Wait Time - PWA

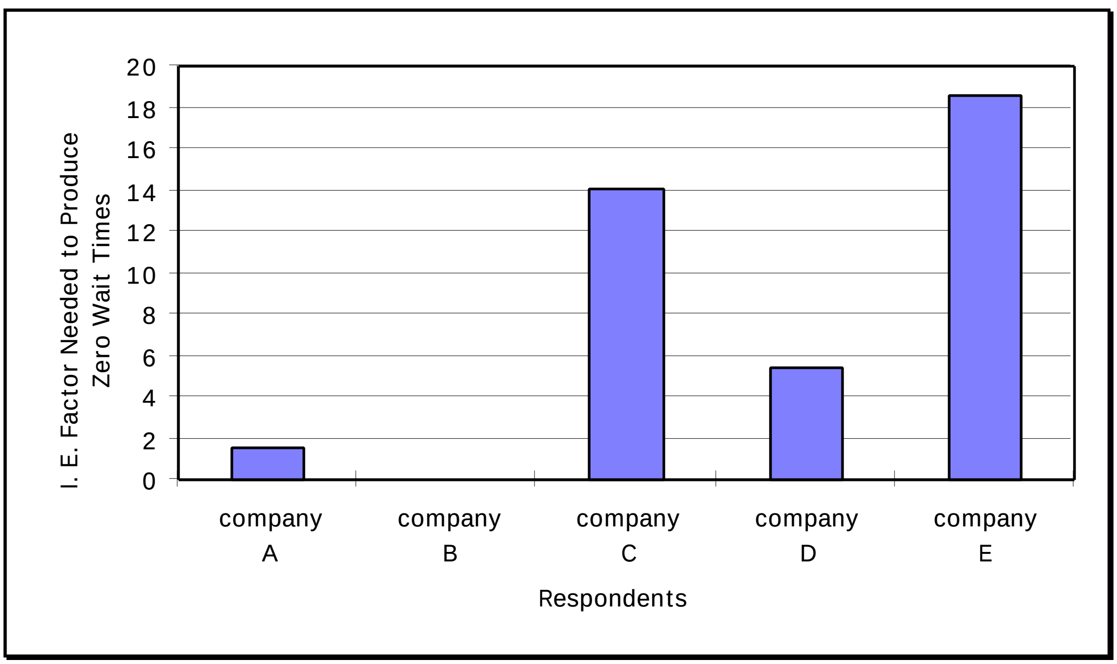

Figure 33: Electronic Sector Realization Factor for Zero Wait Time - Chassis

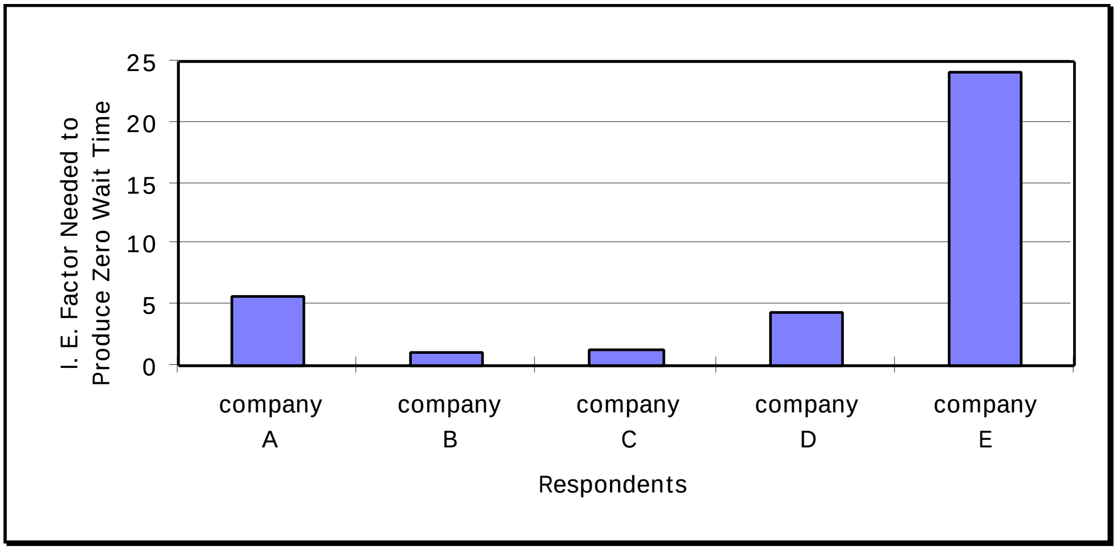

Figure 34: Electronic Sector Realization Factor for Zero Wait Time - Cable/Harness

4.3.3 Process Type

As mentioned earlier, the data can be grouped by process type. We have looked at two process types in this data. Job shops have been addressed earlier. In this analysis, we will address flow shops and dedicated lines. In Figure 35, we see that the flow efficiencies of flow shops and dedicated lines vary drastically. In job shops, there could be other factors which could affect wait times. In a flow shop or a dedicated line, wait time is not confounded by other factors (like in a job shop process) and may be classified as waste. Therefore, an analysis of flow shops and dedicated lines can yield more information about the components of wait times. We identified fourteen data points that were from flow shops or dedicated lines. As was mentioned earlier the flow efficiencies of these locations varied from less than one percent to just over eighteen percent as can be seen in Figure 35. We would like to evaluate the wait times associated with this process type.

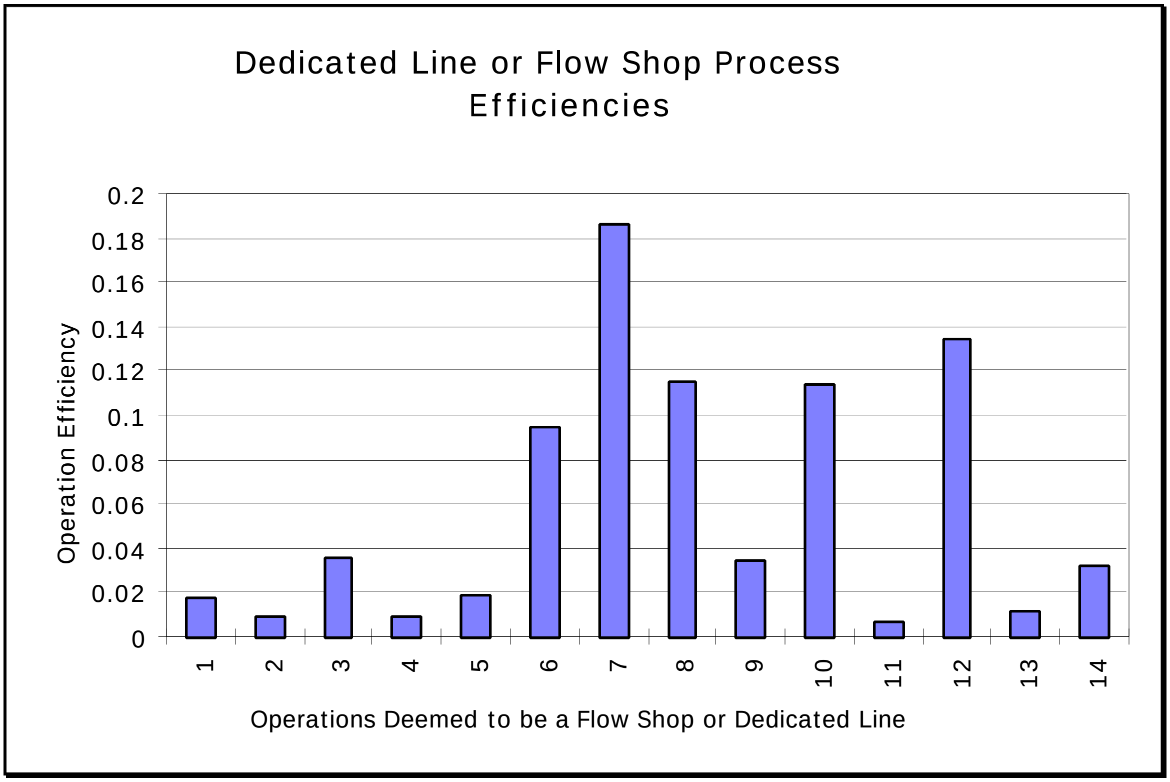

Figure 35: Flow Shops or Dedicated Line Flow Efficiencies

First, we explored the strength of travel distance on flow efficiencies. If there is a strong relationship, then it is reasonable to say that travel delay is a major component of wait time. Using the data set for flow shops and dedicate lines only, we can see in Figure 36 that there is a slight decrease in flow efficiencies as the distance traveled is increased. However, this is not a strong relationship. Therefore, it is reasonable to say that travel delay is not the major component of wait time. Since the lot sizes in this process are small, the lot processing delay is also not the major component of wait time. Therefore by process of elimination, storage delay is the major component of wait time.

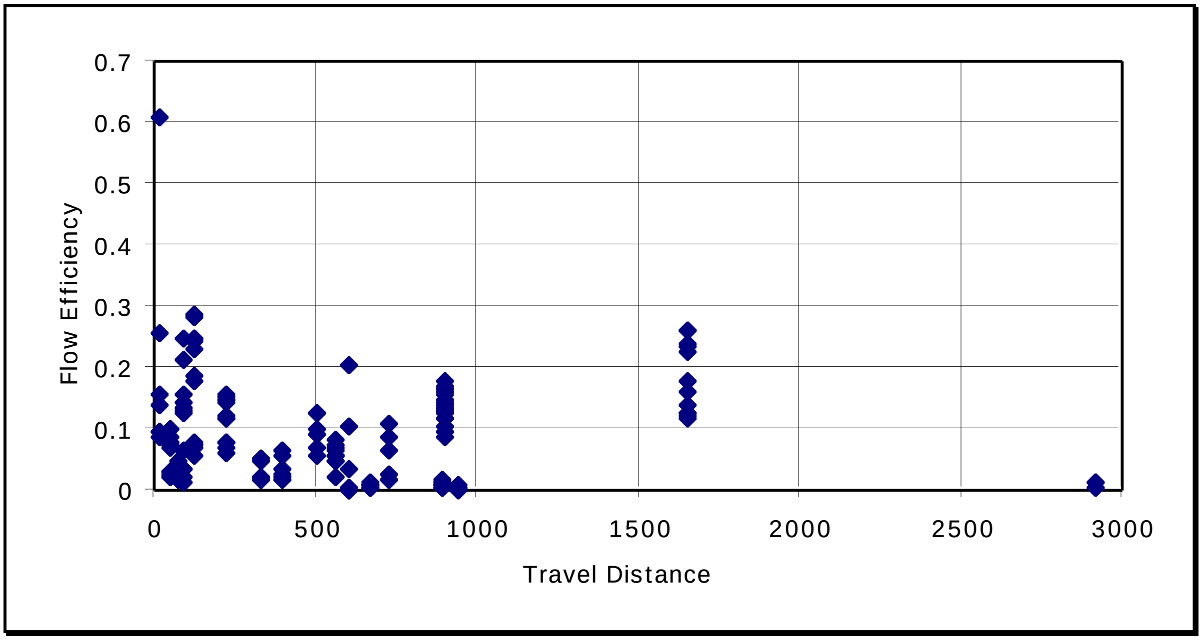

Figure 36: Flow Shop and Dedicated Line Flow Efficiencies versus Travel Distance

5. Flow Benchmarking Other Industries

In order to understand how this industry relates to other industries a continuing effort is underway to characterize flow efficiency information in other industries. The important characteristics to differentiate these flow efficiencies are process type, production rate and industry source (commercial or defense). The process of obtaining this information is tedious but has been progressing over the last year. There are a few commercial data points that can be inserted for comparison. Table 4 shows the commercial examples obtained to date.

Process Type	Flow Efficiency	Parts Produced/yr	Part Type
Assembly Cell	66.7%	252,000	Steering gear assembly
Fabrication Cell	56.3%	307,650	Engine part (connecting rod)
Dedicated Line	33.8%	307,650	Small engine assembly
Fabrication Cell	28.0%	315,070	Steering gear fabrication
Batch Production	0.1%	2,058,000	Steering gear fabrication

Table 4: Commercial Industry Flow Efficiencies

Even with our limited commercial industry benchmarking a few comparisons can be made. For those fabrication or assembly operations performed in some sort of a cell process layout the range of flow efficiencies is provided in Table 5. It is clear that the number of parts produced in the commercial examples is far above what is experienced in the defense industry. However, the commercial example with the highest flow efficiency does not have the highest volume.

Process Type	Flow Efficiency	Parts Produced / Year
Assembly or Fabrication Cell (commercial and defense)	13.5 - 66.7%	280 - 315K
Assembly or Fabrication Cell (commercial only)	28.0-66.7%	252K - 315K
Job Shop (commercial and defense)	0.02 - 0.80%	4 - 2,058K
Job Shop (defense only)	0.02 - 0.80%	4 - 9,860

Table 5: Commercial and Defense Industry Flow Efficiencies

6. Work Instruction Benchmarking in the Electronic Sector

The members of the electronic sector wanted to benchmark the level of effort expended in the development of work instructions. A set of questions was inserted into the questionnaire which asked for the I. E. standard hour content of the work instruction and the time it took to develop the work instruction. Since not all work instructions are written to the same level of detail, a rating was asked from each of the respondents on a scale from 1 to 10 depicting the average level of detail provided in the work instructions. A rating of 1 to depict a very low level of detail comprising minor adjustments to the blue print and no written instructions. A rating of ten indicated a complete redraw of the blue print with detailed written instructions. The results of this benchmarking is in Figures 37 and 38. In Figure 37, the reported time to create work instructions per I. E. standard hour of work detailed in the work instruction is presented. In Figure 38, this same information is presented but normalized by the degree of difficulty factor rating (1-10).

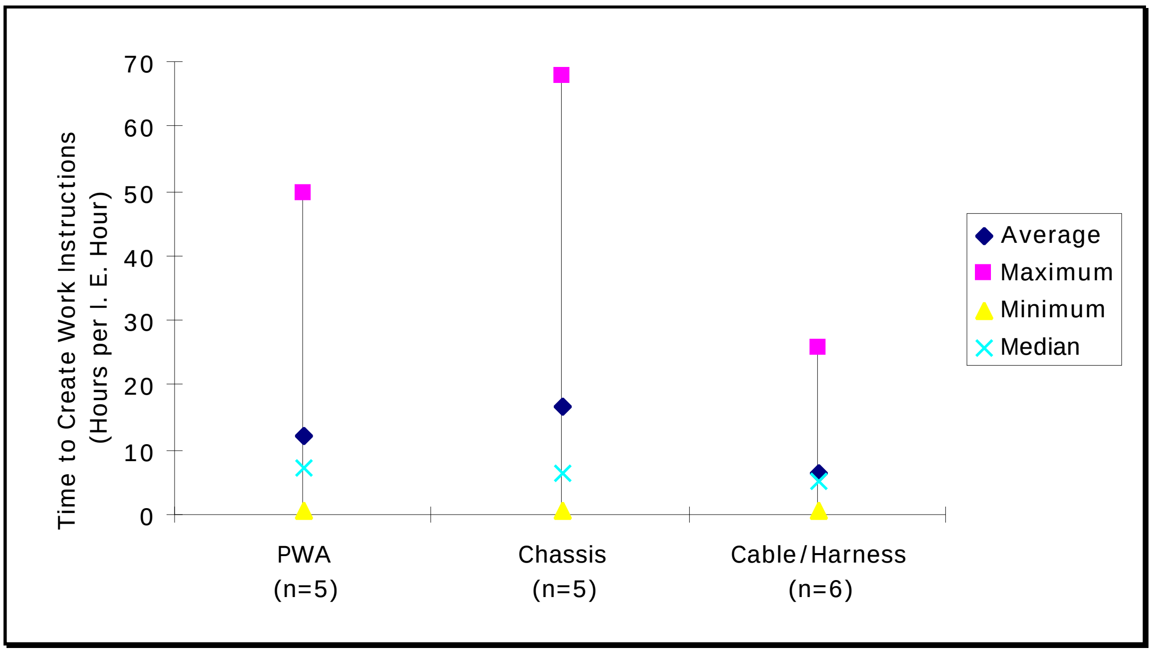

Figure 37: Work Instruction Creation

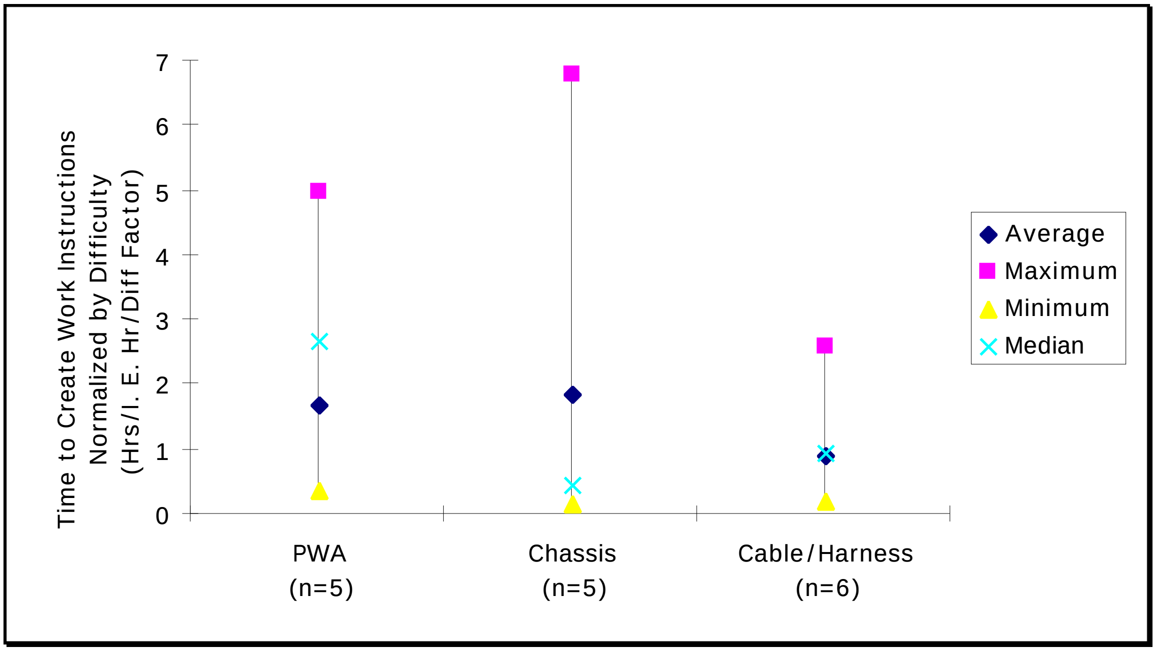

Figure 38: Work Instruction Creation (Normalized by Degree of Difficulty)

The questionnaire also explored the degree of distribution of paperless technology in the electronic sector. In each of the parts explored in the questionnaire; PWAs, chassis, and cables/harnesses, the method that work instructions were presented to the workers was captured. There were three categories that summed to 100 percent for each respondent: interactive paperless, paperless, and manual. Interactive paperless was defined to be where operators utilized a CRT screen to view the work instructions and the computer prompts the operator for input such information as quality or operation status. The paperless category also had operators utilizing a CRT to view work instructions but they were not prompted by the computer for any information. In the manual work instruction system, only a paper method of communicating was used.

For each of the parts benchmarked the range of use of the three categories of presentation of work instructions to workers is presented in Figures 39 through 41. Although each respondent's use of a presentation system had to add to 100 percent the grouped results do not have this same characteristic. However, the median values will reflect reasonable information about use of this technology in the electronic sector of the Lean Aircraft Initiative.

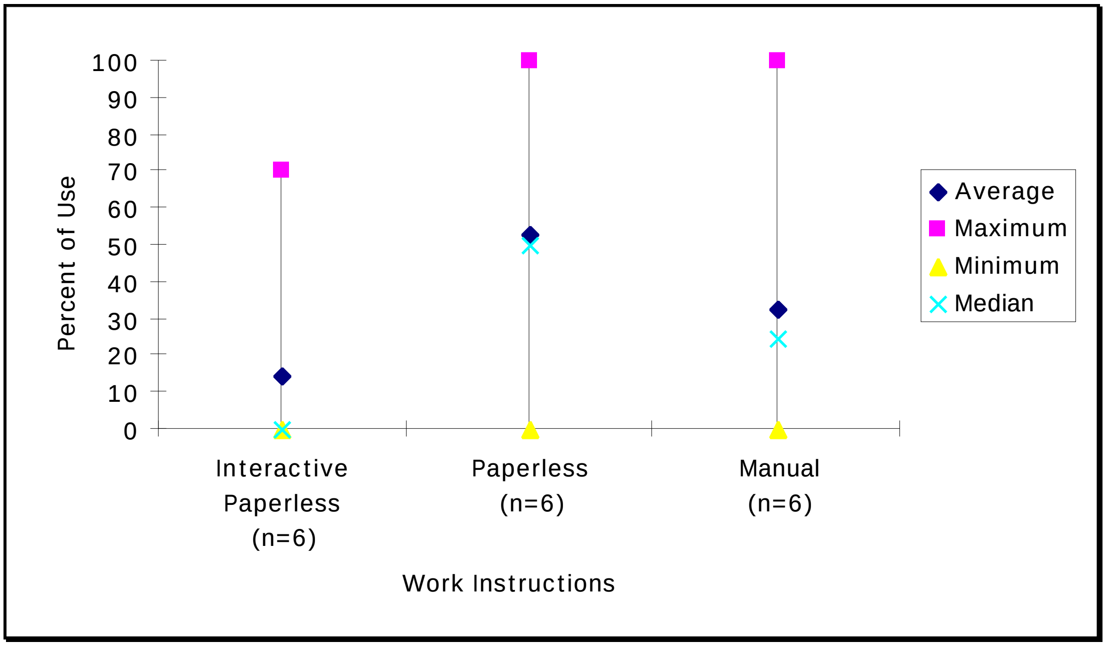

Figure 39: Distribution of Paperless Technology in Printed Wiring Assemblies

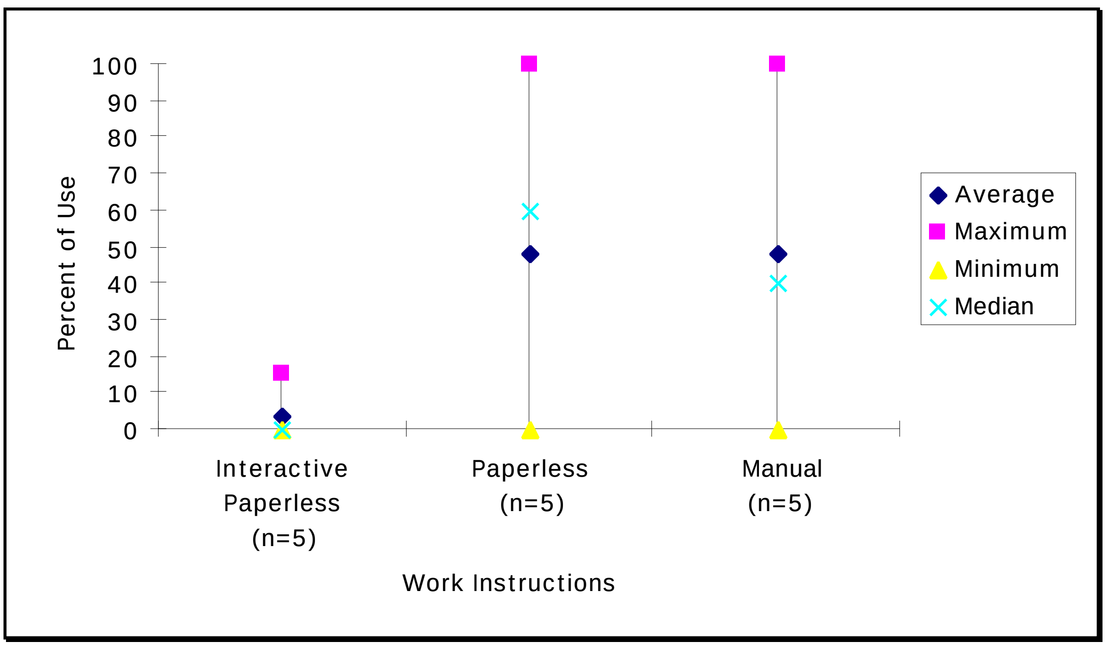

Figure 40: Distribution of Paperless Technology in Chassis

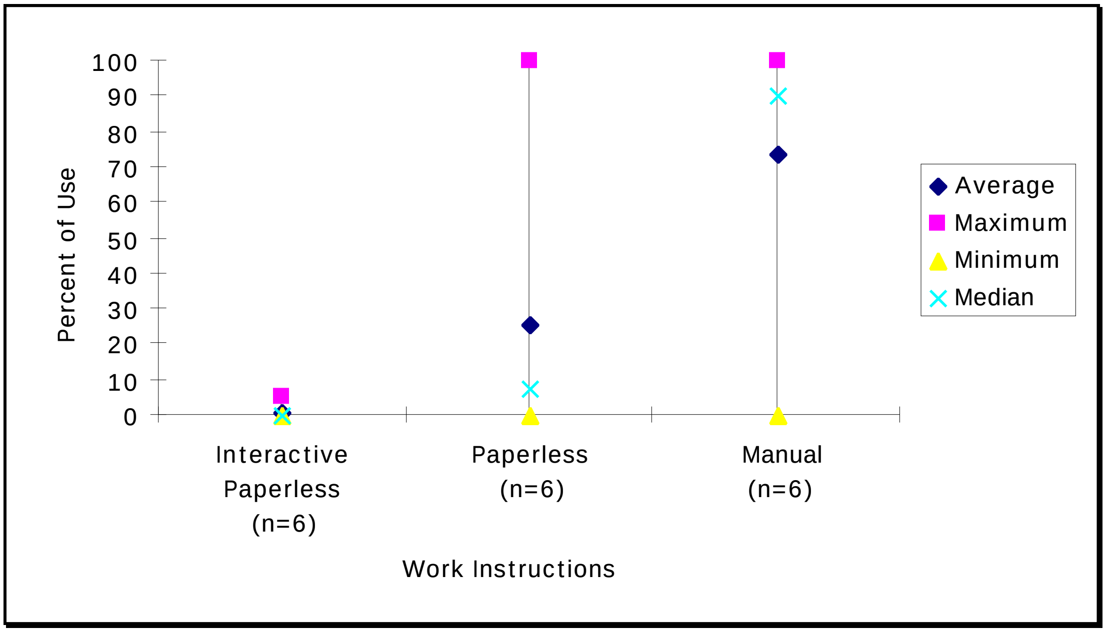

Figure 41: Distribution of Paperless Technology in Cables/Harnesses

7. Conclusions

This benchmarking effort has produced, for the first time, a set of data to characterize the flow of generic products through the defense aircraft industry production systems. We will first offer some conclusions relative to product cycle time then offer observations and conclusions relative to other data collected in the questionnaire.

Initially we collected data on the differences between parts used in this benchmarking effort expecting that the characteristics of the parts could influence the benchmarking metrics. We found that the small portion of time associated with touch labor working on the parts was overshadowed with the amount of time the part waited during the cycle time. For those products benchmarked from the airframe sector which collected data for the entire lot size the proportion of time devoted to fabrication was normally less than 5 percent (see Figure 42). In the engine sector the fabrication time (as

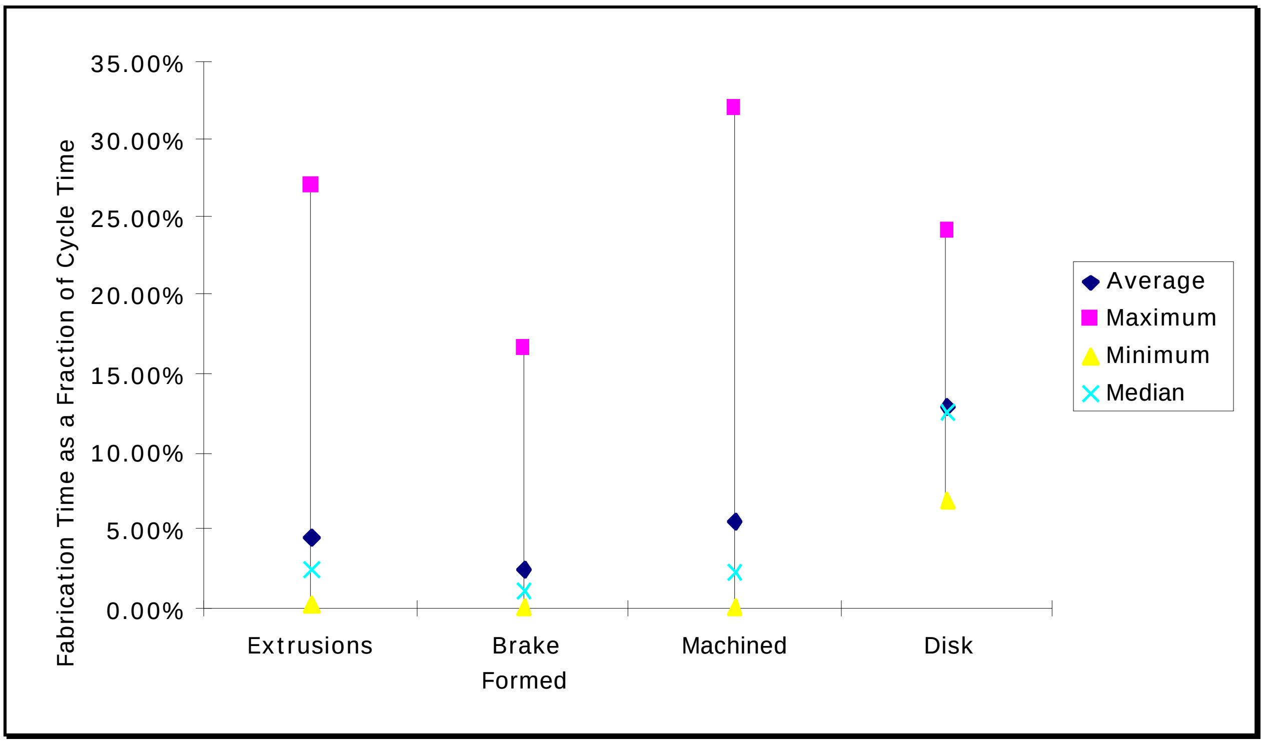

Figure 42: Fabrication Times as a Fraction of Cycle Time for Entire Work Orders

a percentage of cycle time) is higher but still less than 13 percent. In the electronic sector where data was collected by part rather than by lot, the fabrication time proportion of cycle time was less than 5 percent for PWAs and less than 14 percent for chassis (see Figure 43). Since the average fabrication time was not greater than 14 percent and in most cases less than 5 percent, it was small compared to the total cycle time. From this information we felt comfortable assuming that the part differences had little influence on the part flow characteristics studied. Therefore, we did not find it necessary to normalize the data based on differences between parts, and we concluded that an apple to apple comparison was achieved within each sector simply through the judicious choice of the parts for which we gathered data.

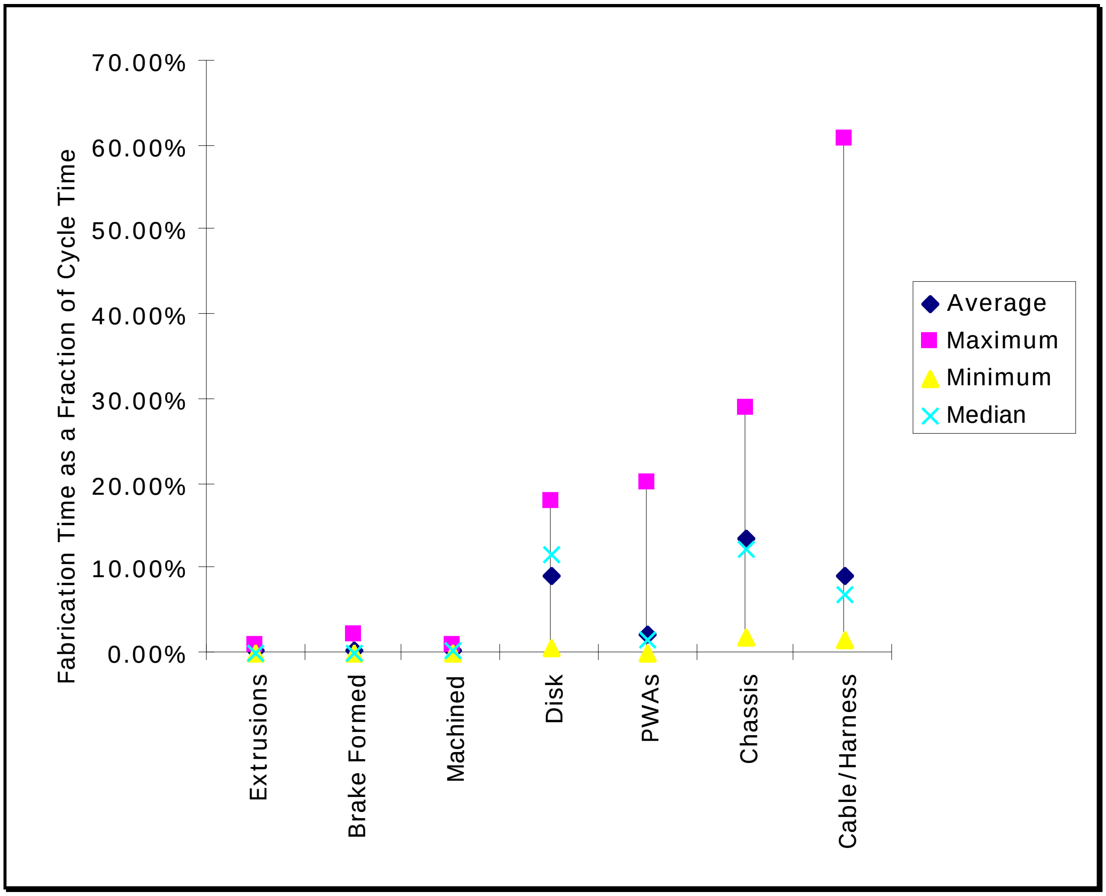

Figure 43: Fabrication Time as a Fraction of Cycle Time for Individual Parts

We also determined that we could compare flow efficiencies across sectors using a judicious definition of flow efficiency. Therefore, we feel that we have been able to establish an industry benchmark useful for comparing factory flow characteristics in part fabrication. As you can see in the section on comparisons to other industries, this metric is also useful for comparison to other industries using common process types.

The flow efficiency from the commercial industry indicates a much higher production volume. However, just having high volumes does not guarantee high flow efficiencies. The company producing the highest number of parts is actually performing like the defense industry in the job shop type of process. This particular commercial example is processing parts via a batch processing system similar to a job shop. Therefore, the most likely association with flow efficiencies is not the production volume but the type of process being used.

In the analysis, we found that the flow efficiency in the various sectors varied as shown in Figure 44. What does this mean? Let's take an example of a product that takes 100 hours to be produced, i.e. the cycle time is 100 hours. As shown in the second column in Figure 44, the product is actually being fabricated only 18.7 hours in the best case (flow efficiency of 18.7%) and in the worst case of only 1.2 minutes (flow efficiency of 0.02%) out of the 100 hours.

Sector	Flow Efficiency	Fabrication Time for 100 Hr Cycle Time
Airframe	0.02% to 0.8%	1.2 min to 48 min
Electronic	0.02% to 18.7%	1.2 min to 18.7 hr
Engine	0.7% to 13%	42 min to 13.0 hr

Figure 44: Defense Aircraft Industry Flow Efficiencies

As we have learned in our studies however, there are differences depending on the type of process that is used to make the products. If we differentiate the flow efficiencies by process type, we see some different results as indicated in Figure 45. As we have noted previously, the flow efficiencies of job shop type processes can be influenced by other factors such as facility capacity, optimization techniques and lot sizes. However, in the case of flow shops or dedicated lines, the actual design of the process is for enhanced flow where the part path and operation machinery is optimized for processing these parts (or family of parts). In these dedicated lines or specifically designed flow shops, any wait time is non value added time. Therefore, the flow efficiency in the flow shop or dedicated line is an accurate measure of the efficiency of this type of fabrication system. What is striking in this picture is the wide variation in flow efficiencies in this process type. We can see that the variance ranges almost as low as experienced in the job shop type processes yet ranges to a high of nearly 20 percent. This suggests that the process design alone does not improve efficiency. Using our 100 hour cycle time example as before, we see that the times devoted to fabrication are also eye opening.

Sector	Flow Efficiency	Fabrication Time for 100 Hr Cycle Time
Job Shop	0.02% to 0.8%	1.2 min to 48 min
Flow Shop/ Dedicated Line	0.1% to 18.7%	6 min to 18.7 hrs

Figure 45: Defense Aircraft Industry Flow Efficiencies by Process Type

We were able to support our hypothesis that the larger the lot size or the distance traveled the lower the flow efficiency would be. Besides the theoretical linkage of flow efficiency to lot size, our analysis showed that there was a strong correlation between flow efficiency and the lot size . We also saw that there is a rather drastic reduction in flow efficiencies when the distance the part travels is greater than 2000 feet. We did note that the larger distances traveled is more characteristic of a job shop process which could influence this result.

In a lean production system, the amount of wait time would be reduced to the lowest level possible. One of the factors that effects wait time in a production system is the process layout. The best performance would be expected from a continuous flow process (like oil refining or steel making) followed in order by dedicated flow process (like connected cells producing a dedicated part or group of parts), a shop flow process (like printed wiring board where each operation follows the preceding operation without retracing a path back to previous operations), and job shop (like a machine shop organized by process type where each operation needed dictates where the part travels).

It was striking in our data that there was an overwhelming amount of time in which the products were waiting for something. We characterized this wait time as a fraction of the total cycle time and called it the wait fraction. Although we were not able to directly measure the wait time in the electronic sector, the upper bound on this wait fraction has a median value of 87.6 percent[3]. As you can see from Figure 46 and the previous statement, the preponderance of the cycle time is due to waiting.

Sector	Wait Fraction
Airframe	96%
Electronic	Max 25% to 98%
Engine	87%

Figure 46: Defense Aircraft Industry Wait Fractions

The components of wait time that we could dissect were, transportation delay, lot processing delay and storage delay. Through our analysis, we were able to ascertain that the majority of the wait time is due to storage delay. We found that the lot processing delay did not exceed three percent of the wait time. Transportation delay

3 The average of the maximum wait fraction was 71.6 percent, however, since most of the respondents were at the high end of the wait fraction the more representative figure for the sector is the median value.

did not appear to predominate in the electronic sector, and through informal interviews with the other sectors, it was determined that it was not a major factor as well.

During the course of this benchmarking effort we saw very few respondents that tracked their actual cycle times. Even if the data was available to the respondents, actual cycle time was not considered an important metric to track and trend over time. Most of the scheduling systems in operation were based on Materials Requirements Planning (MRP) or Manufacturing Resources Planning (MRP II). These types of planning systems are not optimized for work scheduling but were consistently used to load the factory operation. Because MRP or MRP II systems assume infinite capacity, there often is more work introduced into the factory operation than the system can process.

In the airframe sector, we found that the median time from the issuance of the work order until the time that the first operation was performed was on the order of 23 percent of the total cycle time to build the part. This would suggest that either the production scheduling system is issuing orders without regard to system capacity or availability. Long waits prior to starting production could indicate a dysfunctional scheduling system.

One principle of a lean production system is waste minimization. We contend that the time that a product sits without value being added to it is waste. Although there may be other good reasons for products waiting during the process (particularly in job shop type processes), in general wait time is waste which should be minimized. Therefore, lean production systems will have little wait time as the product goes through the production system.

One of the major objectives of the Lean Aircraft Initiative is the reduction of cycle time. From our research, the largest component of that cycle time is wait time. Therefore, the most impact on cycle time reduction will come from wait time reduction. In order to accomplish wait time reductions, it is necessary to know product actual cycle time and to understand the components of this cycle time. If the major contributors to wait time can be determined, then process improvement efforts can be initiated to reduce or eliminate the wait time causes.

In previous Lean Aircraft Initiative case studies, we have found organizations that have done just this. They have concentrated process improvement efforts on cycle time reduction by attacking the major elements of that cycle time. In some cases cycle time reductions came from initiating new less time consuming operations. In other cases, the cycle time reductions came from the removal of wait time in the system. In these studies, we have shown that organizations that trend cycle time learn to understand the factors that affect this cycle time. We have observed that as these organizations reduce their cycle time that the variability of the cycle time also reduces making the production system more predictable. A more predictable production system is then able to plan and utilize resources for a better performing bottom line.

With the additional information gathered in the questionnaires, different conclusions can be drawn depending on the sector. This effort produced data in a number of areas such as process control methods, quality information, equipment uptime, worker training, operator inspection, employee suggestions, facility data and in the electronic sector time to create / modify work instructions. The following paragraphs provide some observations and conclusions relative to this information.

In the airframe sector, the distances traveled by the parts were quite high averaging from 2416 to 5023 feet. Much of this distance was dictated by the location of processing equipment (heat treat or paint). Steps with process control ranged from a low of 9.3 percent to a high of 81.4 percent and averaged from 44 to 55 percent. However, the predominant process control method (at about 80 percent) was process verification consisting mostly of manual inspection. SPC was used for process control in only about 16 percent of the process steps. Although not all respondents reported quality information, we were able to gather some information on defects per standard hour yielding averages of .22, .04 and .24 for extrusions, brake-formed parts and machined parts respectively. Using the average standard hour content of the parts this indicates that there is some problem in 1 out of every 10 extrusions, 1 out of every 50 brake-formed parts and 1 out of every 2 machined parts.

In the electronic sector, the distance the parts traveled was the smallest of the three sectors averaging about 600 feet for PWAs and chassis, and less than 300 feet for cables / harnesses. We asked and were provided information about equipment uptime and found it averaging 93.5, 96.8 and 98.6 percent for the PWAs, chassis and cable / harnesses. Responses to questions about worker training documented about 50 to 60 hours of skill training per year. This sector provided the most information on quality. The average values of hours of rework compared to actual manufacturing hours yielded 11 percent for PWAs and 7 percent for chassis and cables / harnesses. Operators inspected a large portion of their work showing median values of 85, 98 and 99 percent for PWAs, chassis and cables / harnesses. The percentage of employee suggestions implemented was 78, 80, and 56 percent for PWAs, chassis, and cables / harnesses. This resulted in an implemented suggestions per employee average of about 8 percent. Time to create / modify work instructions averaged about 7 to 17 hours per hour of standard work to be performed. These values differed due to difficulty of the work instruction set.

In the engine sector, cells and flow shop layouts were used most prevalently. About a third of the processes used to make turbine disks use CNC equipment and when SPC is used it is used in about one third of the process steps. This sector uses very little facility space for WIP storage and specific areas for rework or repairs. This sector exhibited the most conversion from job shop process layouts to cell manufacturing layouts.

Further research needs to be done to establish the benefits of improving the flow efficiency of operations particularly in low volume situations. This future research should detail the cost benefit of flow efficiency improvements. Just improving cycle time may not be a sufficient stimulus for improving fabrication or assembly operations. Managers in the defense industry are seeking to understand the cost benefits before embarking on flow efficiency or cycle time improvements. They wish to know how much benefit can be realized so they may structure how much they can support changing. However, we do have evidence that some members in the defense aircraft industry have established the importance of continuous cycle time improvements and they are actively pursuing efforts to reduce their cycle times to fabricate and assemble products.