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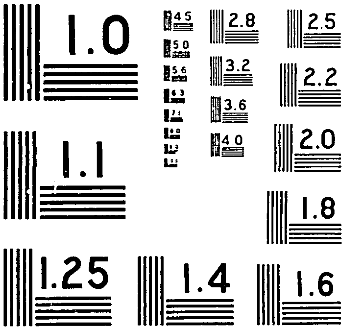

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Application of Cellular Manufacturing to Low-volume Industries

by
Paul W. Dul
B.S., Mechanical Engineering and Materials Science, University of Connecticut (1988)

Submitted to the Department of Materials Science and Engineering
and to the Sloan School of Management
in Partial Fulfillment of the Requirements for the Degrees of

Master of Science in Materials Science and Engineering
and
Master of Science in Management

in Conjunction with the
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Abstract

Traditionally, aerospace and other low-volume manufacturers have structured their operations around process center layouts. This layout was adopted to cope with the high product mix and low-volumes with which these companies were faced. Product layouts, with their high levels of capital investment, were not adopted by low-volume manufacturers due to their high contribution to unit cost.

The key to achieving a product layout lies in generating sufficient volume over which to distribute capital costs. Two approaches can be taken to increase volume: (1) design parts such that they are substantially similar and (2) design manufacturing systems such that they are flexible enough to produce a wide variety of parts while incurring little to no set-up time between parts. These two approaches allow economies of scale and scope to be generated even in low-volume industries.

This thesis presents a case study undertaken at the Boeing Commercial Airplane Group's Renton Division. It shows how cellular manufacturing can be applied to low-volume products for substantial gain. The study focuses on the production of doors for the 737 and 757 aircraft in Renton's Door Responsibility Center (DRC). It projects that cost savings in excess of 50% are achievable via cellular manufacturing. It also contends that cellular manufacturing can be extended across detail part fabrication to attain significant cost reductions throughout Boeing's product line.

While the study points to specific cost reductions, most of which are precipitated by decreases in labor expense, it also stresses that their are many less easily quantifiable gains to be made via cellular manufacturing. These must also be considered when evaluating the merit of cellular manufacturing projects.

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Acknowledgment

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Chapter 1: Introduction

The Boeing Commercial Airplane Group, in an effort to reduce both the cost and lead-time for the production of its commercial aircraft, is in the process of restructuring its operations with the formation of "responsibility centers". Each center will have responsibility for the design and manufacture of a group of products. The first of these centers, the Door Responsibility Center (DRC), was established in March 1993 to design and manufacture doors for the 737 and 757 aircraft [1]. Though significant planning preceded the implementation of the DRC, much has yet to be learned. In this respect the DRC is viewed by the company as a learning laboratory with which to influence the design of future responsibility centers. This thesis focuses on the applicability of cellular manufacturing techniques to achieve aggressive cost and lead-time reductions in the DRC and in responsibility centers in general.

Chapter 2 discusses two different manufacturing strategies: the process layout and the product layout. The traditional theory is that low-volume producers operate most efficiently when organized in a process layout, while high-volume producers are most efficient under the product layout. This chapter discusses the soundness of this traditional reasoning and suggests a more efficient operating mode for low-volume manufacturers.

Chapter 3 presents a case study of a proposed application of cellular manufacturing within the DRC. This chapter identifies detail parts as a primary cost driver and suggests a method for reducing their cost. It shows how a number of similar parts (door stop-fittings) may be grouped into a part-family and how modest redesign can be used in conjunction with flexible manufacturing systems to generate significant economies of scope and improvements in performance.

Chapter 4 analyzes the cost impact of cellular manufacturing. It shows that significant, quantifiable gains can be achieved via part-families and cellular manufacturing techniques. Estimates of required investment and expected cost reductions are made. A net present value analysis is also presented as an attempt to quantify the gains which are possible.

Chapter 5 closes with a review of major findings and suggests that the gains made in this case study are not unique. In fact, many opportunities to realize similar gains exist throughout Boeing and in many low-volume manufacturers both inside and outside the aerospace industry.

1.1 Goals and Motivation for Stop-fitting Cell

1.1.1 Background of the Door Responsibility Center

Facing mounting price competition from its primary competitor, Airbus, the Boeing Commercial Airplane Group (BCAG) found its market dominance in jeopardy during the early nineties. To combat this growing threat BCAG began to explore ways to decrease both the cost and the lead-time to manufacture its commercial aircraft. A major initiative toward this end is the implementation of responsibility centers. Responsibility centers contain all the disciplines required to design and manufacture a line of products. Typically these disciplines include: product definition, industrial engineering, process engineering, manufacturing, materials management, materiel, human resources, finance, and various administrative and support functions. Such a structure, with small decentralized functional groups, is in stark contrast to Boeing's traditional organization of very large, centrally controlled, functionally oriented groups. The intent of the responsibility center concept is that a multi-disciplinary organization under the direction of a single manager will eliminate the linkages (and inherent miscommunications) between the current functional silos, thus decreasing design and production lead-times and, ultimately, costs.

In order to gain experience with responsibility centers, BCAG formed a team to plan such a center for the production of doors for its 737 and 757 aircraft. After a six month planning effort, the Door Responsibility Center was established by upper level management as a pilot program in March of 1993. The DRC was given a directive to reduce overall cost of door production by 25%. The DRC took up residence in the Renton Division's Door Shop and proceeded to integrate product definition, materiel, human resources, finance, and support personnel into the existing Door Shop structure. While all organizations were co-located in the DRC office/shop space, many of its personnel still reported to their functional organizations. As a result, lines of authority were sometimes unclear.

All detail components of which the 737 and 757 doors were comprised were designed in the DRC. While designed in-house, all detail part fabrication took place outside of the DRC in either Boeing's Fabrication Division or at vendor locations. In essence, the DRC was a design and assembly area with all detail parts being purchased and then integrated into the final product.

1.1.2 Scope and Intent of Project

The intent of this project was to evaluate the applicability of cellular manufacturing in achieving the DRC's cost and lead-time reduction goals. Building on previous research by Kevin Bartelson (LFM '93), who suggested that stop-fittings be produced via cellular techniques, this project considers the applicability of cellular manufacturing to low-volume production, using the stop-fitting part-family as case study example [2]. The case study takes a detailed look at the relative costs and benefits of producing stop-fittings in the cellular mode. This analysis assesses necessary product design changes, material selection, equipment specification and layout, and financial soundness.

1.2 Thesis Findings

1.2.1 Applicability of Cellular Manufacturing

This case study clearly demonstrates the potential benefits which can be derived from cellular manufacturing. To date, most applications of cellular manufacturing have been in high-volume industries such as the automotive industry. This case shows that the same principles which allow high-volume producers to achieve significant gains in quality and cost reduction can indeed be applied to the aerospace industry and other traditionally low-volume manufacturers. The primary benefit of the cellular approach is derived by unlocking economies of scope and scale which have always been present in the manufacturing system, yet have been overlooked. By strategically exploiting these economies, companies such as Boeing will be able to drive cost reductions, improve quality, shorten cycle-times and overall lead-times, reduce inventory and improve the organization's responsiveness to both customer-driven and internally-driven product changes. While these claims seem bold, one need only refer to the dramatic improvements in the US automotive industry to realize that these benefits are not only attainable, but critical to survival in light of increasingly fierce competition.

1.2.2 Delegation of Authority within Responsibility Centers

In order to achieve the type of gains which are possible via responsibility centers (and more fundamentally, part-families), it is important to empower specific responsibility center leaders with the authority to control all the functions contained within the responsibility center. In this way, responsibility centers will be able to make the changes necessary to improve operations and, ultimately, control their own destiny. It also increases the level of accountability to which responsibility centers and their leaders may be held. While they probably will never vanish entirely (nor should they), it will become increasingly vital for central organizations to relinquish much of their decision making authority to responsibility centers if the formerly enumerated gains are ever to be realized. The reality is that long-term survival necessitates the redistribution of power. This matter may be BCAG's largest obstacle to making responsibility centers a reality.

Chapter 2: Production Layout

This chapter describes the process layout typical of the aerospace industry. It highlights some of the inefficiencies of this strategy and introduces the product layout as a more efficient production system for many applications.

2.1 Process Layout

2.1.1 Application in Low-volume Industries

The aerospace industry has traditionally viewed itself as a low-volume producer. As such, it has organized itself in a process layout characterized by large batch sizes and significant work-in-process as well as finished goods inventory. Process layouts are generally more efficient when there is wide variation in the product mix. Grouping machines by function results in less idle time for an individual machine and hence greater machine utilization [3]. This approach makes perfect sense in a world where the primary metric is machine utilization. However, as insightfully illustrated by Goldratt in *The Goal*, utilization rate may be a meaningless and even dangerous metric [4].

Common theory holds that process layouts are best applied to low-volume production, while product layouts (machining systems dedicated to the production of a single part) are best applied to high-volume production [5]. See figure 2.1.

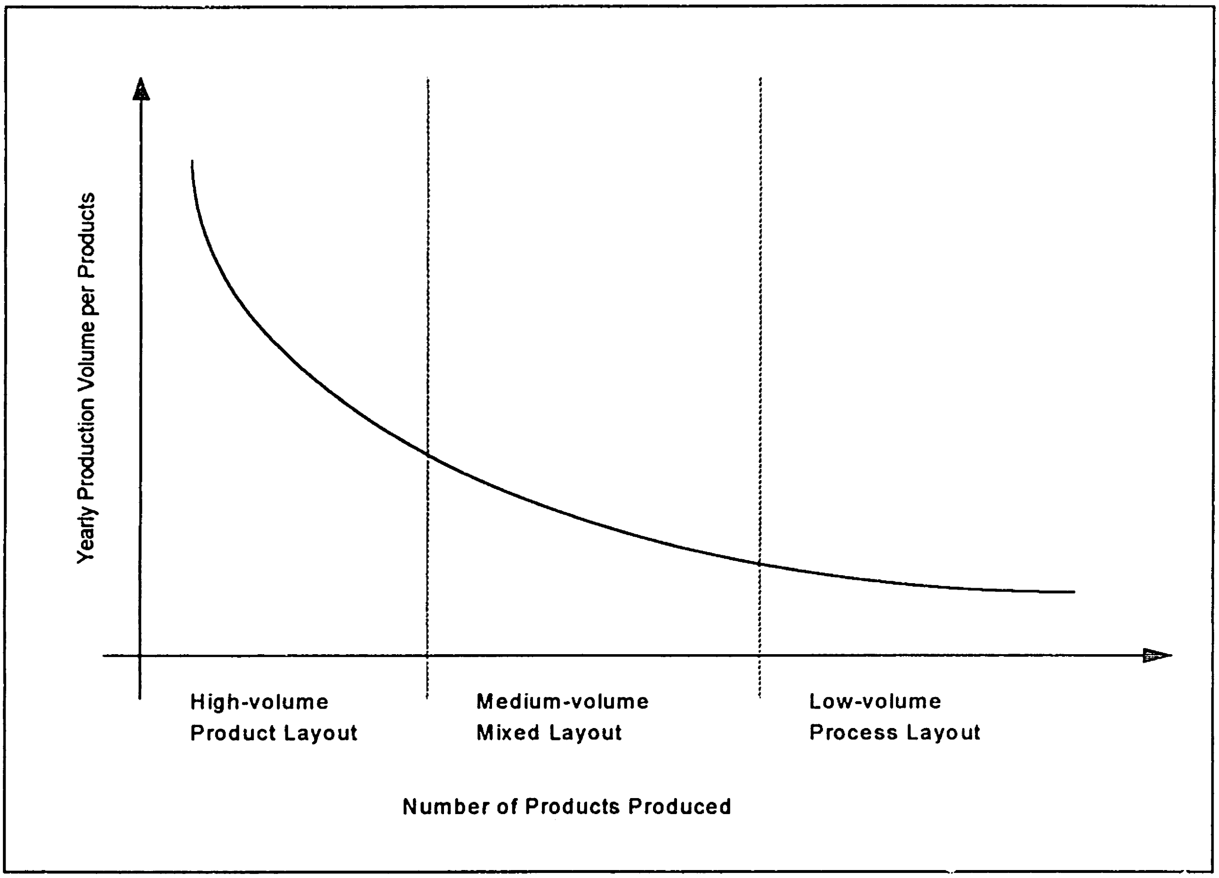

Figure 2.1 Traditional Production Layout Planning

This thesis proposes that the traditional theory of manufacturing layout is outdated and that many low-volume industries can increase their efficiency by organizing their operations into product layouts.

2.1.2 Inefficiency of Process Layouts

The primary problem with process layouts is their innate high cost. The typical process layout consists of machines grouped by function. For example, milling machines are grouped in one area, lathes in another, finishing operations in yet another area, etc. Parts that require a given processing sequence travel over relatively long distances, in large batches (typically 50 - 100 parts or more) to each functional area. Before a part is processed in any given area, it usually must wait a for a machine to become free. Then it must wait for all the parts in its batch to be processed before it can move to the next operation. Due to the size of functional centers, they are often located a significant distance from each other. Therefore, transportation times can be significant, especially in the common case where a delay is incurred prior to transport. It is easy to see that process center layouts result in rather substantial lead-times due to time spent in queue waiting for a machine to become available, long batch processing times, and significant transportation times and delays. In fact, it is not uncommon for queue time to account for 95-99% or more of a product's lead-time.

A natural consequence of process layouts and the associated long lead-times is a high level of work-in-process and finished goods inventory. Inventories are responsible for a number of costs in the production system. First, since inventory is valuable there is the obvious cost of money issue. Also, inventories add to the amount of floorspace needed to produce a product. The additional floorspace manifests itself in additional construction costs, maintenance costs, taxes and utilities expense. There is also a real labor cost associated with holding inventories in that the inventory must be stocked, tracked and later distributed. All these problems are magnified for products which are large and require considerable space and effort to store. Of necessity, work-in-process (as well as finished goods) inventory must grow in proportion to lead-times. Thus, the only way to cut inventory is to cut lead-times.

Process layouts are responsible for inhibiting product improvements. Although less easily quantifiable than other losses, this is a serious concern. When producing via a process layout with up to 20 months or more of inventory in the pipeline, it necessarily will take 20 months for a change made today to be reflected in a finished part. In extreme cases, change can be incorporated more quickly by flushing (scrapping) parts in the pipeline and backfilling with new parts (in this case the work-in-process inventory has, in effect, become obsolete). There are two significant costs to this approach: first, the obvious cost of obsolescence associated with scrapping 20 months of inventory; and second, the perturbations of the manufacturing / scheduling system which are caused when the backfilled parts are expedited through the manufacturing system. In many instances the opportunity to make a change will be foregone because the cost associated with high inventory levels more than offsets the benefit of the change. This situation serves to frustrate individuals striving to improve products and eventually leads them to terminate their improvement efforts. In this situation the employee is robbed of the satisfaction of making a meaningful contribution and the company loses the benefit of the product improvement.

Process layouts also stymie process improvement efforts. In order to make changes which will result in significant improvements in product quality and/or cost, it is necessary to have detailed knowledge of all the operations which comprise a given process *and* to have systemic knowledge of the manufacturing process as a whole. In theory, the process engineer possesses both the detail and systemic knowledge. In practice, however, this knowledge is fragmented among many individuals (n production workers, where n is the number of operations which the part must undergo, and the process engineer at a minimum). Thus, the fragmentation of knowledge inherent in process layouts makes significant process improvements difficult, if not impossible, to attain.

Worker morale also suffers under the process layout. Production workers in a process layout are denigrated to the role of machine operators who simply tend a machine. The typical operator sees a continuous stream of many different parts. He knows nothing about what happens to the part before he receives it or what will happen to it after he is finished. He has his instructions for each part, performs his operation, and then places the part in an outgoing area where it waits to be taken to the next anonymous operation. A common refrain on the shop floor is "parts is parts" [sic]. In other words, it doesn't really matter what work operators are given - they are essentially drones and will perform their operation on whatever parts happen to come their way. The implicit assumption is that if it were possible to automate the equipment there would be no need for the operator. Not only is this demeaning to the worker, it is an incredible waste of human talent. Production workers are the owners of detailed operation knowledge. By denying them the systemic knowledge of the process they are rendered incapable solving more significant process problems. This is a true lose-lose situation. The workers are addled and frustrated because they are not allowed to see the complete picture and the company loses the benefit of the workers' intellect.

There are some valid reasons for instituting a process layout, such as the extreme flexibility demanded by job shops. However, process layouts have been adopted rather haphazardly and exist today in many situations where much more efficient options are available. The use of process centers in low-volume, semi-repetitive production represents such a misapplication. The following section describes a more efficient production strategy for low-volume, semi-repetitive environments.

2.2 Product Layout

2.2.1 Cellular Manufacturing

The issues raised in the previous section seem to point to two culprits: large batch sizes and fragmentation of processes. Cellular manufacturing provides a production strategy which attacks both these issues. Cellular manufacturing espouses the application of a product layout rather than a process layout. In a pure product layout, machines are organized such that all the equipment necessary to produce a finished part are located in the same area and operated by either one worker or a team of workers. This approach not only eliminates long transportation times and delays, but also vests both the detail knowledge of individual operations and the systemic process knowledge with either a single individual or a cell team.

The second thrust of cellular manufacturing is batch size reduction. Proximity of equipment and balancing of operations within the cell allow production in small batches or lot-sizes. Instead of moving in large batches over long distances from operation to operation, parts flow in small batches (ideally a lot-size of one) over very short distances within the cell. Cycle-times of individual operations are balanced, ensuring a smooth, steady flow of parts. Lot-size reduction results in less in-process inventory and decreased lead-times (which allow finished goods inventories to be cut). Thus, cellular manufacturing effectively induces significant inventory reductions.

2.2.2 Barriers to Cellular Manufacturing

Cellular manufacturing proves to be a very efficient production technique, however, the capital expenditure necessary to construct a cell can make a large contribution to unit cost. The impact of capital on unit cost is inversely proportional to the volume of parts processed in the cell. When the volume of parts produced in the cell is high, the impact of capital expenditures on unit cost drops. Thus, the crux of the problem is generating enough volume such that the capital expense contribution to unit cost is low.

Clearly, from this perspective, volume requirements pose a very serious constraint to the adoption of cellular manufacturing. In the automobile industry the volume constraint is easily overcome since it is inherently a high-volume industry. Low-volume industries such as aerospace have been more resistant to the adoption of manufacturing cells due to volume issues. Since most parts produced for use in aircraft are made in relatively low-volumes, it is difficult to justify dedicated manufacturing cells due to their high contribution to unit cost. The goal, therefore, for low-volume manufacturers is to expand the effective cell volume. There are two basic keys to expanding cell volume: 1) designing commonality into the parts so that their differences are transparent to the manufacturing cell, and 2) designing flexibility into the cell so that it can easily accommodate a large degree of product variation. Both approaches may be used to increase the number of parts which can potentially be processed by a cell.

Another barrier to cellular manufacturing is the current purchasing strategy of many organizations. It appears that many purchasing organizations optimized their purchasing contracts on a part basis (i.e. bargain for the lowest price on a single part). The result is that potential members of part-families are estranged (spread across many different suppliers). Clearly this approach fails to take advantage of economies of scope which exist between similar parts. Optimization on a part-family basis, allows sizable cost reductions to be realized via capitalization on economies of scope. Obviously the current practice of part level optimization has to end if cellular manufacturing is to be achieved.

Chapter 3: Stop-fitting Part-family

This chapter outlines the planning process for a manufacturing cell to produce stop-fittings for the DRC's 737 and 757 doors. Stop-fittings are the structure on which aircraft doors locate and support themselves with respect to the fuselage (see Figure 3.1). Although there are many different configurations for these fittings, the vast majority are made of various aluminum alloys and would fit into a 4"x4.5"x6" rectangular solid.

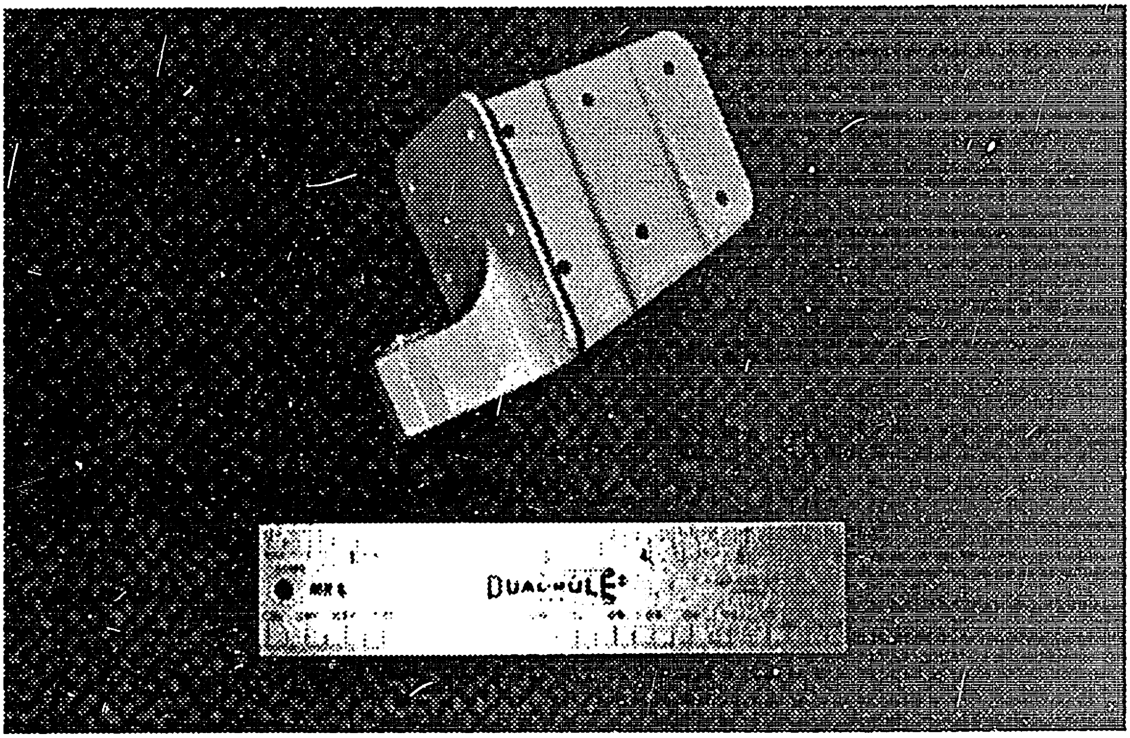

Figure 3.1 Typical Door Stop-fitting

This chapter begins by describing the current state of stop-fitting production and then continues to highlight opportunities to introduce commonality into the design and processing of these parts. Finally, a manufacturing cell is defined which is able to efficiently produce the vast majority of all stop-fittings.

3.1 Case Study Background

3.1.1 Significance of Detail Parts

The DRC, as a pilot program, was under considerable pressure to prove the worth of the responsibility center concept. One obvious proof is cost reduction. BCAG expected the DRC to trim its unit cost for doors by 25%. My objective was to highlight opportunities which would allow significant cost reductions. Figure 3.2 shows the cost structure of the DRC.

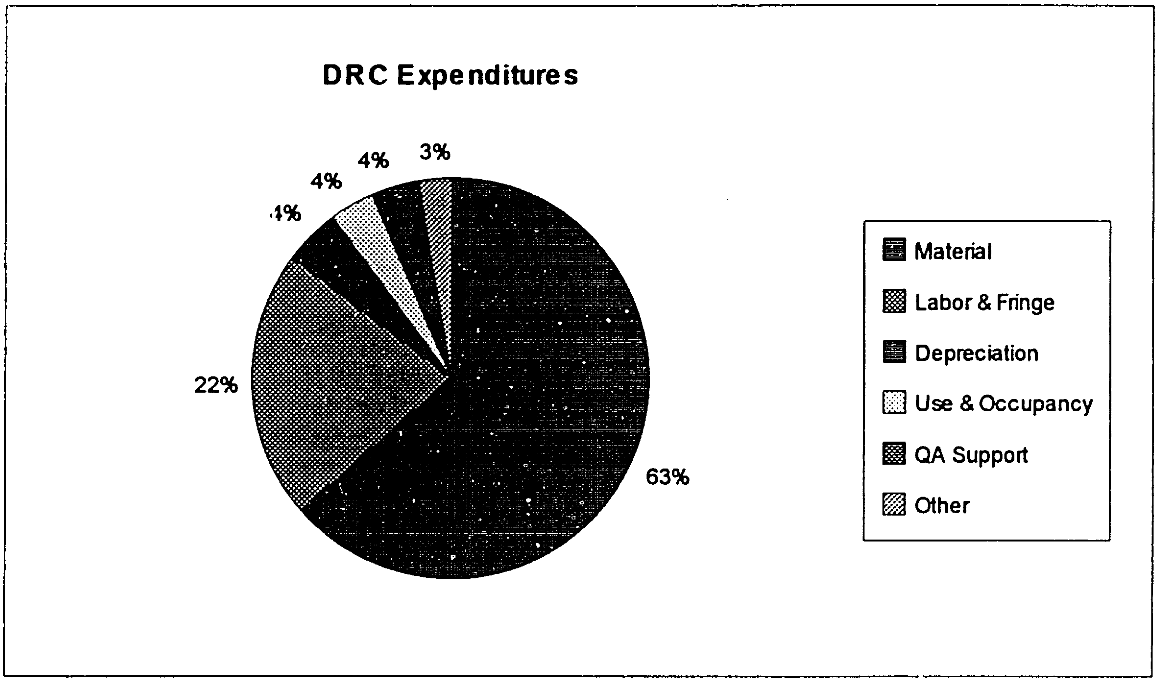

Figure 3.2 DRC Total Expenditures for September 1993

Although these expenditures may vary from month to month and there is undoubtedly some amount of inaccuracy associated with the figures, clearly the DRC's largest expenditure is on material. As such, reducing material (primarily detail part expense) is a natural leverage point for overall cost reduction.

As stated earlier, detail parts manufacture takes place entirely outside of the DRC. While a natural first reaction might be to squeeze price concessions out of suppliers, it is important to first consider what effect Boeing's own design and purchasing decisions are having on detail part cost.

3.1.2 Current State

The DRC makes a total of 16 doors (see Table 3.1). To produce one of each of the 16 doors requires a total of 170 stop-fittings. Currently there are 142 unique part numbers (119 prime part numbers and 23 optional part numbers). Thus, for 170 uses of stop-fittings 119 prime part numbers are required. In other words, each stop-fitting is used, on average, only 1.4 times. Figure 3.3 breaks these numbers down to the level of individual stop-fittings. Considering that most stop-fittings are functionally and dimensionally quite similar, it would seem that a higher level of commonality could exist within the stop-fitting part-family.

	DRC Produced Doors		
1)	737 - Airstair Door	9)	757 - #2 Right-hand Door
2)	737 - Forward Access Door	10)	757 - #3 Left-hand Door
3)	737 - Left Forward Entry Door	11)	757 - #3 Right-hand Door
4)	737 - Left Over-Wing Escape Hatch (L-OWX)	12)	757 - #4 Left-hand Door
5)	737 - Right Over-Wing Escape Hatch (R-OWX)	13)	757 - #4 Right-hand Door
6)	757 - #1 Left-hand Door	14)	757 - Electrical Access Door
7)	757 - #1 Right-hand Door	15)	757 - Left Over-Wing Escape Hatch (L-OWX)
8)	757 - #2 Left-hand Door	16)	757 - Right Over-Wing Escape Hatch (R-OWX)

Table 3.1 DRC Produced Doors

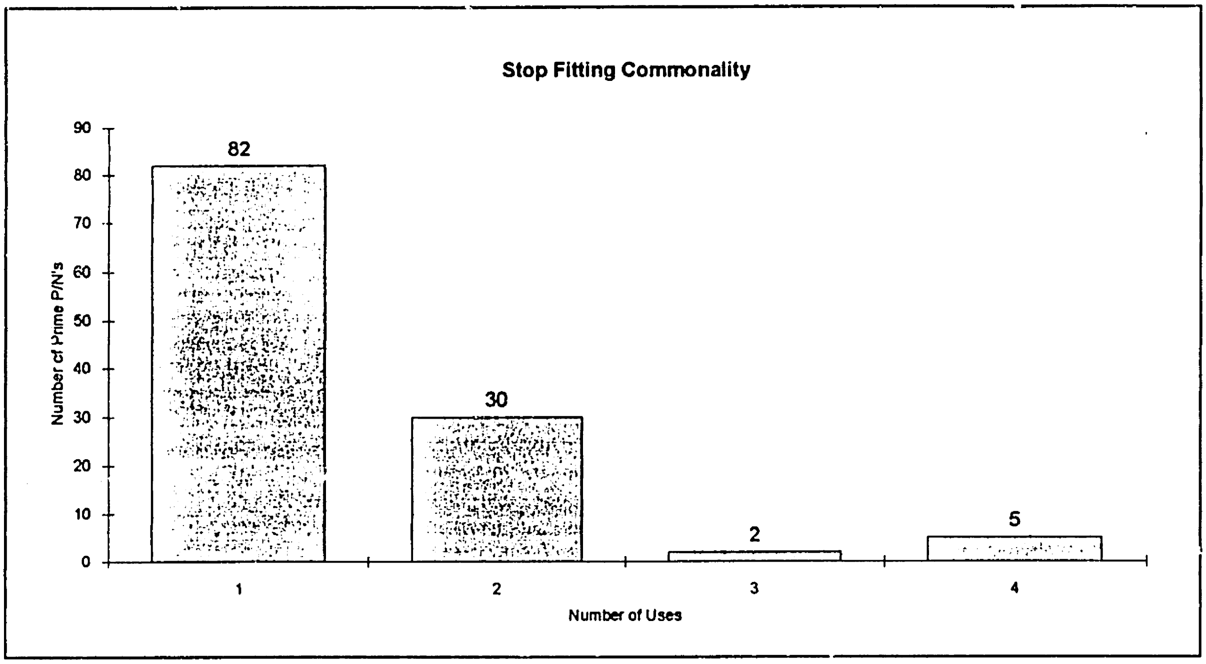

Figure 3.3 Stop-fitting Commonality

A total of 12 different materials are used to produce all 142 stop-fittings. Each material requires a slightly different production process. However, the processes can be grouped into four main categories: die forge, hog-out (machining from forged block or plate stock), extrude, and cast. All processes with the exception of hog-out require some amount of subsequent machining. Figure 3.4 shows the distribution of these four production process categories.

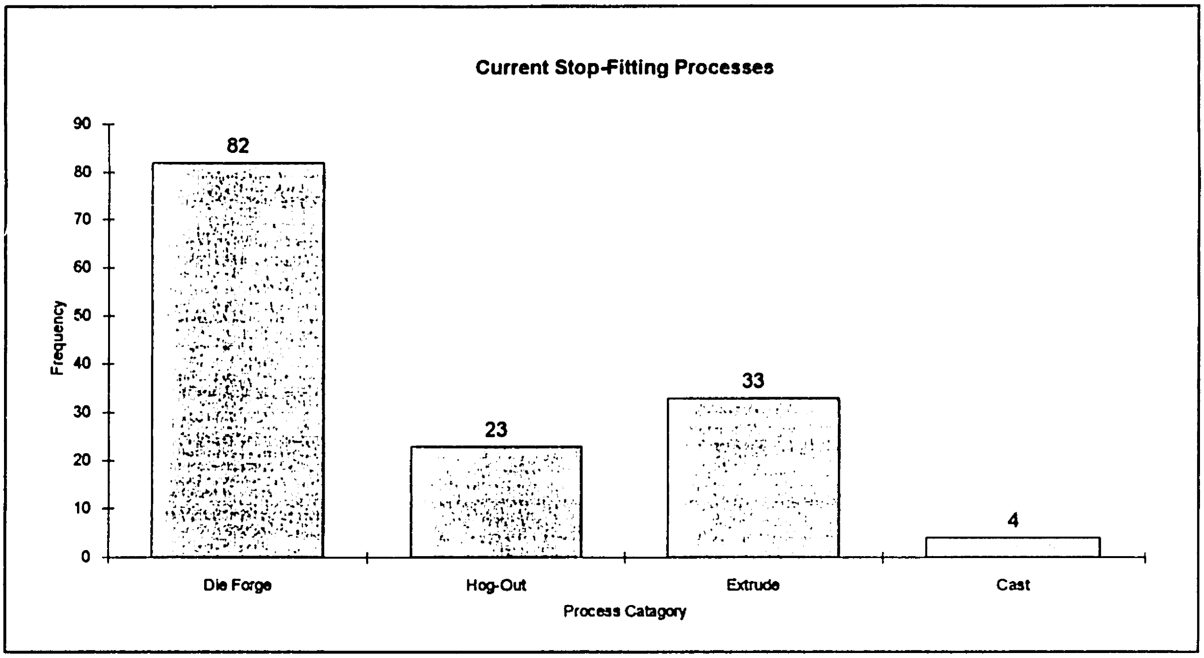

Figure 3.4 Current Stop-fitting Production Processes

Examining the supplier network reveals that there are currently 28 suppliers who are under contract to manufacture 142 stop-fittings. Figure 3.5 shows the distribution of stop-fittings among the various suppliers. On average, suppliers manufacture approximately 5 stop-fitting part numbers.

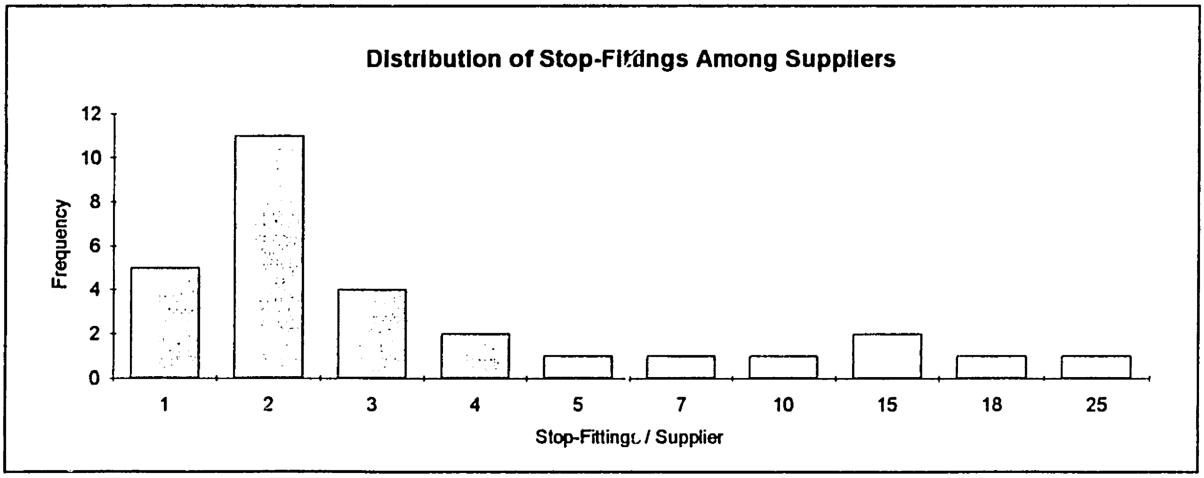

Figure 3.5 Distribution of Stop-fittings Among Suppliers

Finished goods inventory is generally a good indicator of the efficiency of the production and scheduling system. At the time of this study the DRC had an average of more than 16 months of finished goods inventory on-hand. The two worst offenders (part numbers) had 31 and 34 *years* of finished goods inventory on-hand. Another part had 22 years of inventory on-hand. In all fairness, it must be mentioned that these parts belong to a door that had a very significant reduction in rate, however, this example illustrates the inability of the current scheduling system to respond to fluctuations in demand. Looking upstream into the production pipeline, on average there was more than 4.5 months of work-in-process (WIP) inventory. In aggregate, the DRC was responsible for an average of more than 20 months of stop-fitting inventory (see Figure 3.6).

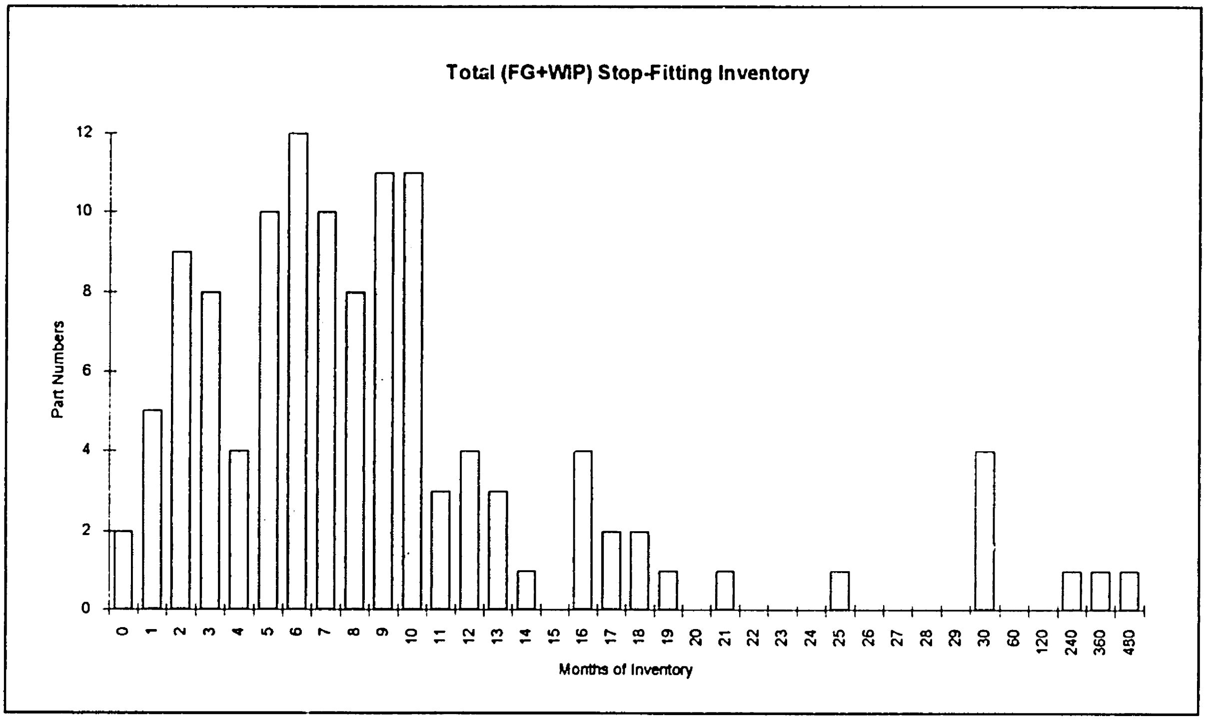

Figure 3.6 Total Stop-fitting Inventory

3.2 Planning the Stop-fitting Cell

3.2.1 Part Commonality vs. Cell Flexibility

As stated earlier there are two techniques which may be applied to increase the volume of candidate parts for a cell: (1) redesign parts for added commonality (i.e. make them more similar), and (2) design flexibility into the manufacturing cell to allow it to accommodate more differentiation among parts. During the initial analysis of the stop-fitting cell the feasibility and cost of both these options were evaluated. Based on past experiences, design changes involving dimensional modifications entail lengthy approval processes which could require a year or more to attain. In addition, once the change is approved there is the issue of expending the substantial inventory already on hand. The costs (both money and time) involved in redesign were deemed to be excessive. Furthermore, the parts were similar enough such that a cell with enough flexibility to handle the designs as they existed could be designed. The level of flexibility required was certainly within grasp of current technology and could be attained at a reasonable cost. For these reasons, cell flexibility was pursued rather than redesigns involving dimensional changes. Although this was the case for this particular cell, it may not always hold true and redesign opportunities should always be considered.

3.2.2 Part-family Identification

For the purpose of this study, all 142 stop-fittings used on the 737 and 757 doors produced by the DRC were initially grouped into one part-family. Then several parts were systematically eliminated from inclusion in the part-family. Seven stop-fittings were made of cast corrosion resistant steel (CRES). Since the manufacturing process for the CRES parts is significantly different from that of aluminum parts they were not included in the part-family. These could be included at a later date providing that they are redesigned for fabrication out of aluminum, however this was not a viable option in the short-run. The production rate for eight parts belonging to the 737 forward access door had been reduced to one door per month as a result of an offset agreement. Current inventory levels provided a supply of parts lasting from 3 to 34 years. Due to the already excessive supply on-hand these parts were also eliminated from the part-family. Lastly, there were a total of 19 optional parts. The final configuration of an optional part was dimensionally identical to its primary counterpart, however, its starting material differed (an optional part might be machined from a forged block, while the primary part would be made from a precision die forging). Since the optional parts would be redundant in a manufacturing cell where all parts are made from the same material and process, these 19 parts were culled from the family. Thus, 108 part numbers remained in the part-family. These parts were made from 10 different aluminum alloys and still required 10 different processes to make all 108 parts.

3.2.3 Process Selection

The manufacturing process chosen for the production of stop-fittings must be quite flexible. Flexibility is defined by the relative amount of time required to change from the production of one product to another. In other words, set-up time must be as short as possible. In turn, short setup times will drive down the economic order quantity (EOQ) so that parts may be produced in small lot sizes eventually reaching a lot size of one. Currently most stop-fittings are produced via a precision forging process. This method forms blanks by pressing hot aluminum billets into steel dies. The aluminum blanks must then be held by a holding fixture and machined to remove flash and/or install various features. The process is inherently inflexible, requiring long set-up times to install die sets. The long set-up times increase the EOQ and lead to large lot sizes. By its nature, the process requires a die set and at least one holding fixture for each part number produced.

This process is inflexible, leads to long set-up times and large lot sizes, and requires a significant investment in tooling and tooling management.

In order to move toward small lot production it is necessary to find a more economically competitive method of production. Today's CNC machines offer a potential solution. CNC machining can rival the overall economy of die forging processes due to its high speed and its ability to maintain very short set-up times. CNC machines can store a large number of different machining programs which can be called up in a matter of less than a minute to machine any part in a given family. Thus the software which defines the cutter path can be set-up almost instantaneously.

The second part of the setup involves the loading and unloading of the part to be machined. Typically each different configuration to be machined would need its own holding fixture. Unfortunately, with 108 different configurations, managing and loading all those tools becomes a logistical nightmare. There are, however, creative techniques which allow the use of a single holding fixture which can be loaded and unloaded very quickly. This technique is called dovetailing and is currently in use at several Boeing Fabrication Division locations. It requires that a dovetail (wedge shape) be machined on the bottom of each starting block. The dovetail slips into a receiving fixture which clamps the raw material firmly in place. Once the raw material is locked into position, the CNC machine can cut the aluminum block to any configuration. The finished part remains anchored to the dovetail via a series of un-machined "bridges" (called tabs) which are cut manually once the CNC machining is complete. When the CNC machine has finished, the operator simply unloads the piece, cuts the tabs using a die grinder, and reloads the CNC machine with the next piece of raw material. This technique will dramatically reduce set-up times, lot sizes, and tooling requirements.

Due to its many advantages, the proposed method of manufacture for the cell will be CNC machining from either forged block or plate stock, in conjunction with a dovetail fixturing technique.

3.2.4 Material Selection

Currently ten different materials are used to produce the 108 parts in the part-family (see Figure 3.7). The logistics involved in stocking and handling ten materials become somewhat involved. Additionally, the possibility of confusing materials and producing a part from the wrong alloy becomes a serious concern.

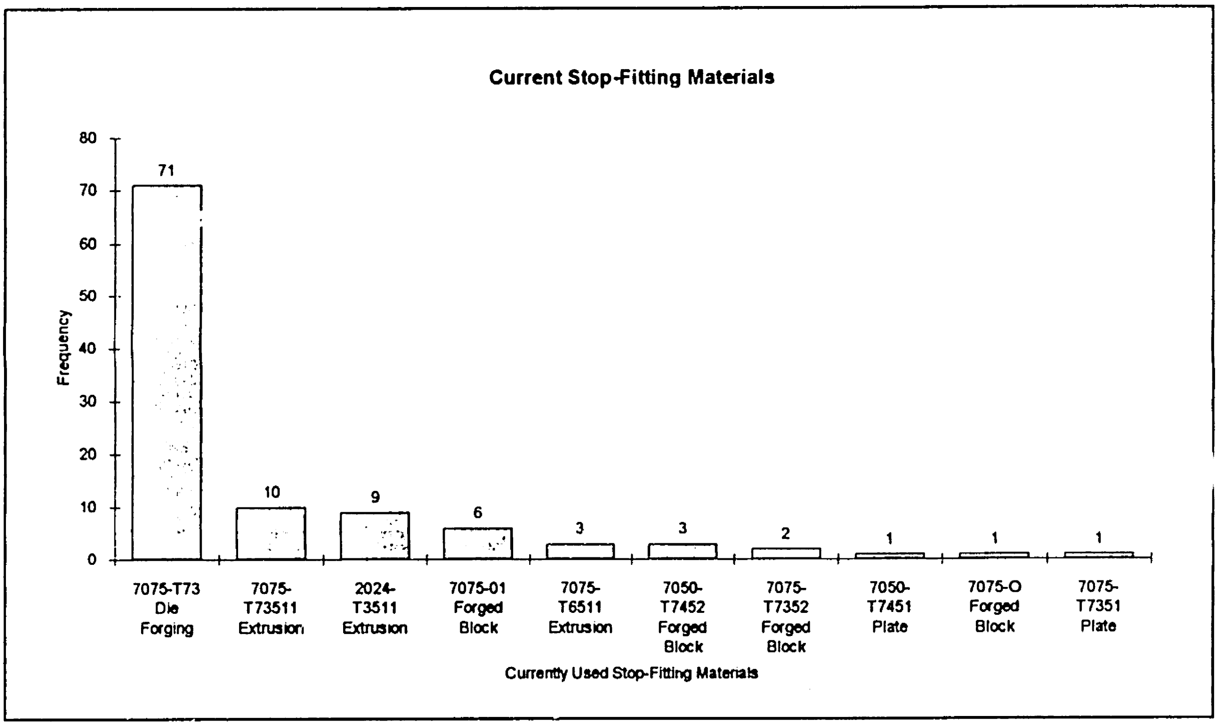

Figure 3.7 Currently Used Stop-fitting Materials

Using just one material to produce the entire part-family would be extremely advantageous in terms of reducing complexity and the possibility for error within the cell. This material must satisfy all design and manufacturing requirements. Additionally, if the material is to be readily accepted for use at Boeing, it must be a Boeing approved alloy.

The approval process requires extensive testing after which the Boeing Materials Technology (BMT) organization publishes static and fatigue allowables upon which Boeing engineers base their designs. Thus, in the short-term, the available materials are restricted to those which either have been approved or are very near approval.

Since the current stop-fitting materials comprise a comprehensive list of available materials, the task becomes one of finding a currently used material which is capable of producing all 108 stop-fittings. Due to the previously discussed inflexibility associated with forging processes, die forgings will not be considered for use in the cell. Extrusions will also be eliminated from consideration since, due to their geometry, many starting configurations would have to be stocked in order to make all 108 parts. This limits consideration to forged blocks and plate stock.

The number of possible materials is further limited when heat-treat considerations are evaluated. Heat-treatment is a lengthy process which requires a cycle-time much greater than that required of the cell. If in-process heat-treatment is required the parts must enter a buffer where they can be batched into larger lot-sizes and processed simultaneously. Such a strategy is contrary to the goal of one piece flow and will cause the cell to carry excess inventory, decreasing responsiveness. Thus, it is extremely advantageous to identify a material which does not require in-process heat treatment. Since both 7075-01 and 7075-O require in-process heat-treatment, they are eliminated from further consideration.

The decision to machine fittings from forged block or plate which does not require an in-cess heat-treatment cycle eliminates many of the currently used materials. The following materials remain in contention for use in the cell: 7050-T7451, 7050-T7452, 7075-T7352, and 7075-T7351. These materials constitute two basic alloys/tempers:

7050-T74 and 7075-T73. Both are aluminum-zinc-magnesium-copper-chromium alloys. 7075-T73 was introduced in about 1960 to counter some of the stress corrosion cracking problems encountered with its predecessor, 7075-T6. The T73 temper is achieved via a precipitation treatment requiring two stage artificial aging. During the first stage, a fine high density precipitate dispersion is nucleated, producing high strength. During the second stage, resistance to stress corrosion cracking and exfoliation corrosion is developed. The additional aging treatment that T73 requires reduces its strength below that of the 7075-T6 temper. In response to the need for a material which exhibited the high strength of 7075-T6 and the stress corrosion cracking resistance of 7075-T73, the 7050 alloy in T74 temper was developed. This material combines the high strength and high resistance of stress corrosion cracking with improved fracture toughness [5]. This material appears to offer significant advantages over 7075-T73, however since it is relatively new, large amounts of in-service data have not been collected. Boeing is currently working very hard to generate and publish allowables for 7050-T74.

The heat-treat cycle which is used to age 7075 to the T73 temper can ensure transformation to T73 to a depth of only 1.5 inches. Therefore, any T73 material used which has a cross section greater than 3 inches (2x1.5 inches) must be aged again after the part is rough machining to a shape having a cross-section less than three inches. Thus, in order to avoid an in-process heat treat, raw material shapes must be carefully selected. Multiple starting configurations would be necessary to ensure that no cross-section exceeds the three inch maximum. Managing several configurations of the same material would add complexity to the system, but is certainly feasible. Multiple configurations are much better than multiple materials since using the wrong starting configuration will produce parts with gross errors which will be easily detected. However, a part machined from the wrong alloy produces an error which is extremely difficult to detect.

Although 7075-T73 is certainly a viable candidate for use in the cell, 7050-T74 represents a better solution. It is stronger than 7075-T73 and does not require an in-process heat-treatment. Thus, a starting configuration of any thickness may be used without having to heat-treat after rough machining. This means that a single starting configuration may be used to machine all parts in the cell. While this may result in excess metal removal for smaller parts, the efficiencies and flexibility gained from a single raw material shape will more than compensate for the waste attributed to excess machining. At the time of this study, firm allowables were not available for the 7050 alloy, however, significant progress was being made, and allowables are expected to be made available by the time of publication. Preliminary data suggested that the allowables would be quite favorable. For evaluation of this material, very conservative allowables were estimated based on the preliminary data.

Due to the promise of 7050-T74 and its ability to reduce cell complexity by offering a single starting configuration without an in-process heat-treat cycle, it is proposed as the material for production of all 108 stop-fittings. This material is nearly identical to the other aluminum alloys considered in terms of weight and cost. Additionally, its static, fatigue and corrosion resistance properties are excellent. In the highly unlikely event that its allowables fall short of expectations, 7075-T73 may be used. However, in this case, the cell will have to contend with defining and managing a number of different starting configurations.

3.2.5 Process Rationalization

Once the process and material have been defined, the currently used process must be dissected and rationalized to ensure that it is as efficient as possible. The current process for the fabrication of stop-fittings from 7050-T74 material is shown in figure 3.8.

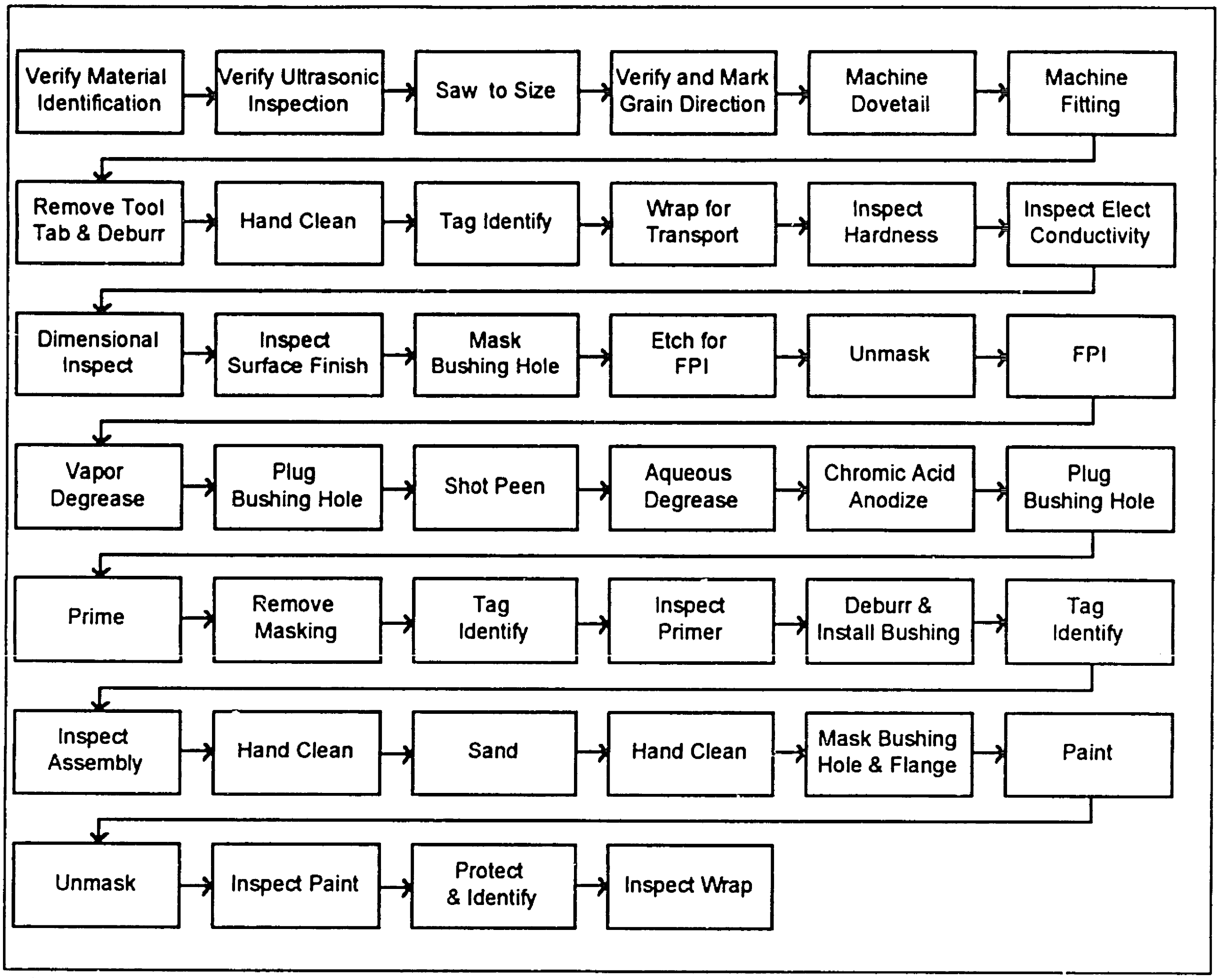

Figure 3.8 Current Stop-fitting Process for 7050-T7451

There are several operations which may be eliminated from the current process. For example, those operations which involve either transport or packaging for transport can easily be omitted, however, some more significant operations may also be eliminated. For example, raw material suppliers can deliver material already cut to the starting shape, thus eliminating the sawing operation at the beginning of the process. Also, the vapor degreasing operation which follows fluorescent penetrant inspection (FPI) and precedes shot-peen may be omitted. The mechanical action of the shot-peen is more than sufficient to remove any residual penetrant. The omission of vapor degrease is particularly significant in that vapor degrease poses a major environmental threat. Also, inspection should be moved to follow shot-peen since shot-peening will cause part distortion.

The anodize process has also been changed from a chromic acid anodize (CAA) to a boric-sulfuric acid anodize (BSAA). This benefits of this change are two-fold. First, BSAA is much safer environmentally than CAA. Second, the degree of end-grain pitting (EGP) and inter-granular attack (IGA) exhibited after BSAA is significantly less than after CAA. Since the reduction of end-grain pitting and inter-granular attack increases fatigue life, replacing CAA with BSAA raises the possibility of eliminating the shot-peen operation (which is included to increase fatigue-life) [7]. Since at this time it is unclear whether this is possible, shot-peening remains as part of the proposed process.

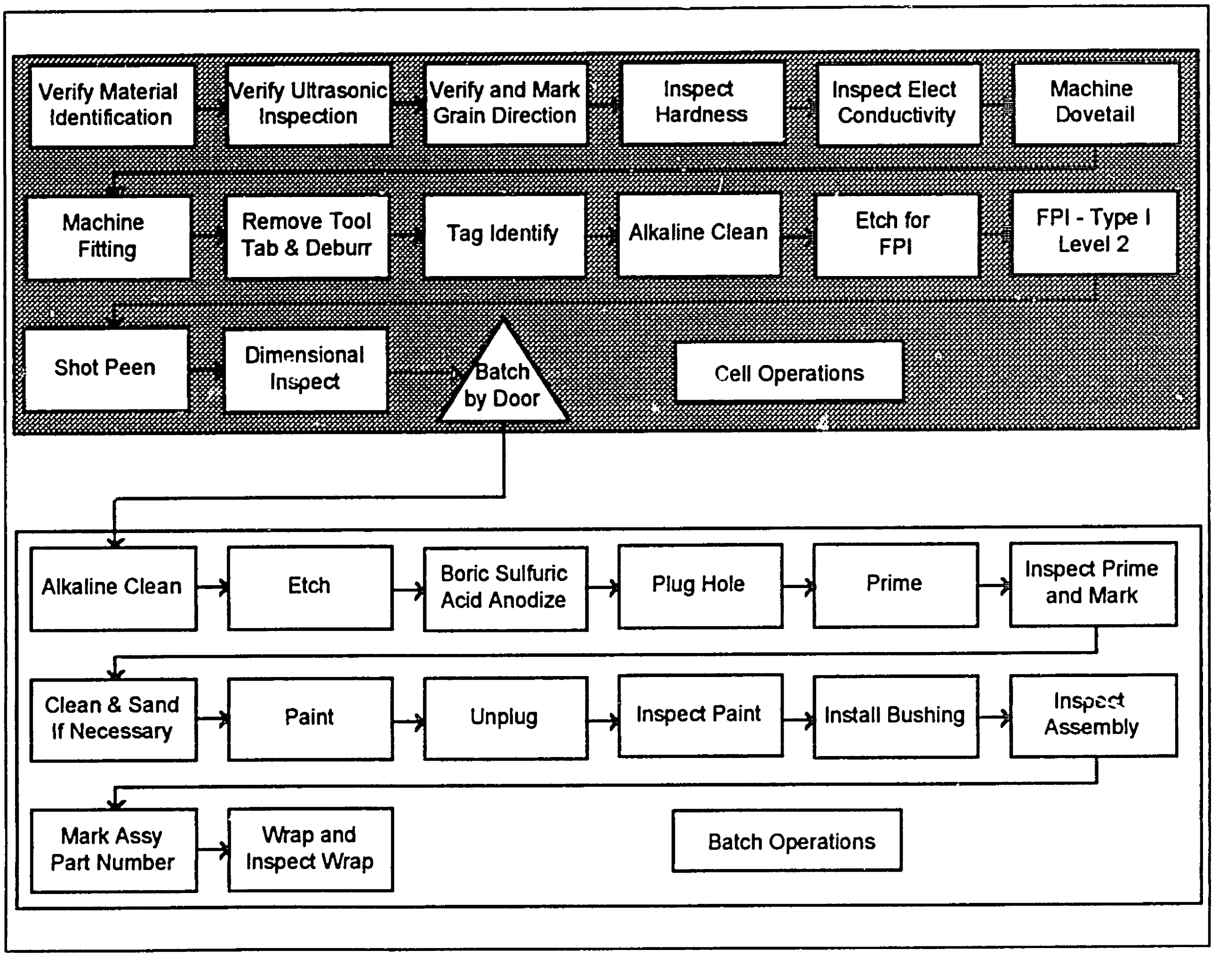

Figure 3.9 Proposed Stop-fitting Process

The resulting rationalized process is shown in Figure 3.9. Those operations which will be included in the cell are shown in the upper (shaded) portion of the figure. The operations extend from inspection of incoming material to dimensional inspection. Stop-fittings will move in lot-sizes of one from machine to machine in the cell. Inclusion of dimensional inspection within the cell provides a rapid feedback mechanism for the cell. Dimensional inspection will quickly highlight quality problems and allow corrective action to take place before a large number of defectives are produced. Ideally, dimensional inspection would take place immediately after the machining operation, however, the shot-peening operation will cause some part distortion to occur and must be followed by dimensional inspection to ensure that parts leaving the cell are dimensionally correct.

After dimensional inspection, parts will leave the cell batched together in kits which include all the stop-fittings required to produce an entire door (door-sets). Batching by door-sets will decrease inventory relative to the current procedure of batching by part number. Once, the parts are grouped together, they will be batch processed though the anodize and paint process. Batch processing will be used for the latter part of the process since the anodize and paint operations present environmental hazards which make them difficult to cellularize. Parts will be sent to stores kitted as door-sets. Kitting in this fashion will simplify the parts storage, ordering and inventory picking process. In essence, fittings will flow though the first part of the process in "single-piece-flow" fashion and through the second half of the process in "single-door-flow" fashion.

3.2.6 Rate Requirements

Once an appropriate process and material combination have been selected the capacity requirements and cycle-time of the cell must be determined. To determine the capacity we must first estimate demand for stop-fittings. Boeing's large backlog allows it to maintain a very constant production rate. Changes in production occur in step-wise fashion and can be predicted well in advance. Thus for the short-run, Boeing's demand can be viewed as deterministic. The capacity requirements of the cell will thus be set according to current production rates.

Currently, (10) 737's and (5) 757's are produced each month. Table 3.2 shows the number of DRC-made doors required for the various models of 737 aircraft produced as well as the number of stop-fittings required to fabricate each door. Table 3.3 provides this same information for 757 aircraft. Note the two different configurations of the 757-200.

Door Type ===>	Airstair	Fwd Access	L Fwd Entry	L-OWX	R-OWX
737-300	~1/3	1	1	1	1
737-400	~1/3	1	1	2	2
737-500	~1/3	1	1	1	1
Cell Fittings / door	12	0	18	6	6

Table 3.2 Model / Configuration Map for 737

Door Type ===>	#1 Left	#1 Right	#2 Left	#2 Right	#3 Left	#3 Right	#4 Left	#4 Right	Elect	L-OWX	R-OWX
757-200 / 1	1	1	1	1	0	0	1	1	1	2	2
757-200 / 2	1	1	1	1	1	1	1	1	1	0	0
Cell Fittings / door	14	14	13	13	10	10	13	13	4	4	4

Table 3.3 Model / Configuration Map for 757

Since the various models / configurations of aircraft require different doors (and thus variable quantities of stop-fittings), model mix must be considered when forecasting stop-fitting demand. Table 3.4 incorporates the information in tables 3.2 and 3.3 with model mix and current production rates to predict the DRC's average monthly demand for stop-fittings.

Model	Fittings / Aircraft	Model Mix	Aircraft / Mo	Ave Fittings / Mo
737-300	34	0.36	10	122.4
737-400	46	0.40	10	184
737-500	34	0.24	10	81.6
757-200 / 1	100	0.50	5	250
757-200 / 2	104	0.50	5	260
		Total Average Fittings / Month		**898**

Table 3.4 Monthly Stop-fitting Demand

According to the forecast in Table 3.4, the stop-fitting cell must be able to produce 898 fittings per month in order to meet the DRC's production needs.

3.2.7 Cell Cycle-time

Both the material and process have been selected for the cell. In addition the bounds of the cell (from raw material inspection to dimensional inspection) and the required output rate have been determined. With this information in hand, it is a simple matter to calculate the required cycle-time (or tact-time) for the cell.

The number of hours per month must first be determined. Assuming that the cell will run three shifts per day, the calculation follows:

Available Production Hours = # Shifts x (Mfg Hours / Shift) x (Mfg Days / Month) x Utilization Factor [ρ]

= 3 shifts x (7 hours / shift) x (20 mfg days / month) x .80

Available Production Hours = 336 hours / month

Given that there are 336 hours / month available, and that the demand on the cell will be 898 units per month, the cell's required cycle-time is as follows:

Required Cycle-time = (Available Hours / Month) / (Required Units / Month)

= (336 hours / month) / (898 units / month)

= .37 hours / unit

Required Cycle-time = 22 min 27 sec = 22' 27"

Therefore, in order to achieve one piece flow, all equipment in the cell must have an effective cycle-time of less than 22 minutes and 27 seconds (i.e. if any operation exceeds the given cycle-time, then additional capacity must be added at that operation).

3.2.8 Equipment Selection, Cell Layout and Performance

Table 3.5 describes the equipment necessary for each operation to be conducted in the stop-fitting cell. For a more detailed description of equipment and justification see Appendix A. Table 3.5 also includes estimates for manual operation time (set-up time), machine processing time and the completion time per unit. This information is used to determine the cell's minimum cycle-time and the total manual operation time per cycle.

Oper #	Operation Description	Equipment	Manual Time	Machine Time	Completion Time
			(min, sec)	(min, sec)	(min, sec)
10	Draw raw material	Incoming area	0' 30"	0' 00"	0' 30"
20	Inspect raw material	Incoming inspection station	2' 00"	0' 00"	2' 00"
30	Machine dovetail	3-axis milling machine	0' 30"	3' 00"	3' 30"
40	Machine fitting	5-axis machining center	1' 00"	20' 00"	21' 00"
50	Deburr	Media finish drum	2' 30"	15' 00"	17' 30"
60	Etch for FPI	Etch carousel	0' 30"	18' 00"	18' 30"
70	Prepare for FPI	FPI carousel	0' 30"	18' 00"	18' 30"
80	FPI	FPI read station	2' 00"	0' 00"	2' 00"
90	Shot peen	Shot peen booth	5' 00"	0' 00"	5' 00"
100	Dimensional inspect	Coord measuring machine	1' 00"	10' 00"	11' 00"
110	Stock as kits	Outgoing area	0' 30"	0' 00"	0' 30"
		Total Manual Time	16' 00"	Cell Cycle Time	21' 00"

Table 3.5 Cell Cycle-time Determination

Since the total manual operation time within the cell is less than the cell's minimum cycle-time, a single operator can perform all the set-up operations in the cell within the cycle-time. Therefore, the entire cell can be tended by just one operator.

In order to minimize excess operator motion and allow the operator easy visual monitoring of all operations within the cell, a U-shaped layout is used. See Figure 3.10. The primary characteristic of the U-layout is that the entrance and exit of the cell are at the same place, in effect returning the operator to the beginning of the cell after completion of the last operation and thereby eliminating wasted motion vis a vis a straight line layout.

In cells where the cycle-time is controlled by manual operation time rather than machine processing time, a U-layout has the advantage of being able to adjust the cell's cycle-time by changing the number of workers in the inner area of the "U". This characteristic allows the cell to respond to changes in production rate. When demand for the cell's products increases or decreases workers can be added or removed, respectively, from the inner area of the "U", thus adjusting cycle-time to meet demand [6]. However, since the stop-fitting cell's cycle-time is already limited by machine processing time it cannot be adjusted in this manner.

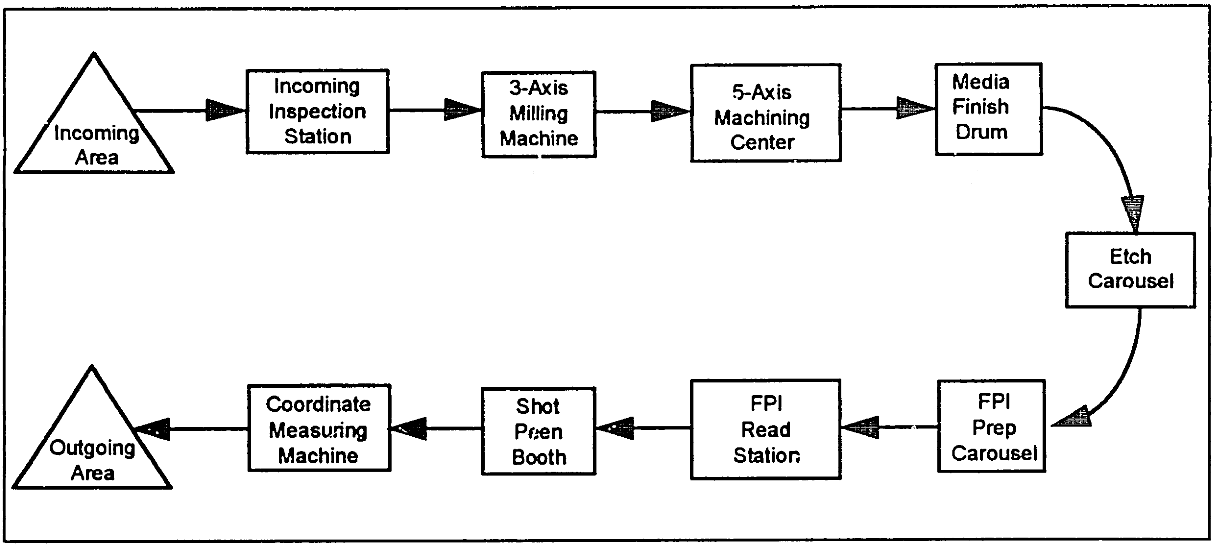

Figure 3.10 - Cell Layout

With a cycle-time of 21 minutes, the stop-fitting cell will have a maximum throughput of 960 units per month, making it capable of producing the 898 fittings / month required by the DRC. Throughput may be increased by working to reduce the processing time at the 5-axis machining center. Since the cell will be capable of one piece flow, the total WIP in the system will be one part in each machine or 9 pieces. These performance metrics are summarized in Table 3.6 below.

Cell Performance Metric	
Throughput	960 units / month
Cycle-Time	21 minutes
WIP	9 units
Labor Requirements	1 person

Table 3.6 Cell Performance Metrics

Chapter 4: Financial Analysis

This chapter analyzes the financial impact of the stop fitting cell by comparing current costs to projected costs. A net present value (NPV) analysis is also presented.

4.1 Document Current Costs

As an example of the cost effectiveness of cellular manufacturing, the stop-fittings will be used to compare current costs with estimated costs of production in the stop-fitting cell. Total capital investment will be considered and a net present value calculation will be used to evaluate the proposed project. This analysis will show that moving to cellular manufacturing can result in cost savings in excess of 50% and a very strong positive NPV.

Due to the proprietary nature of Boeing's cost data, much of the detail analysis is omitted from this document. All costs will be quoted as either aggregate figures or average part costs.

4.1.1 Average Annual Cost of Stop-fittings

To determine the average annual cost of all the stop-fittings included in the stop-fitting cell, two categories of fittings had to be addressed: those purchased from outside vendors and those produced within Boeing's Fabrication Division. Determining the cost of vendor produced parts was a relatively simple matter. Exact cost data was extracted from a database containing current purchase contract information. Determining the cost of internally produced parts was somewhat more complicated. Transfer prices were available, however, they were fraught with obvious errors. Transfer prices were listed as ranging from as little as $10 per unit to as much as $800 per unit. In order to deal with this clearly inaccurate data, all outliers (both high and low) were eliminated from consideration, and an average unit cost was then calculated using the remaining data. This average unit cost was then applied to each internally produced fitting.

Unit costs for vendor produced parts and average unit cost for internally produced parts were multiplied by their respective annual demand to generate a total annual cost per fitting, and aggregated to determine total current annual cost. Using this approach total annual expenditures on stop-fittings was determined to be $1.385 M.

4.1.2 Inventory Holding Costs

There are two inventory holding costs which need to be considered: finished goods inventory and work-in-process inventory. To be conservative, it was assumed that the cost of holding WIP inventory was included in either the contact price of the parts (for vendor supplied parts) or in the transfer price (for internally produced parts). Thus the only inventory holding costs calculated for this analysis are those for finished goods.

Calculation of finished goods inventory was accomplished using a simple methodology. The amount of finished goods inventory was extracted from Boeing's inventory control database and manually spot-checked against actual inventory in the DRC's parts control area (PCA) to ensure accuracy. Totals for each individual part were divided by the monthly demand for the part to determine the number of months of finished goods inventory on-hand for each part number. This data was aggregated to calculate the average amount of finished goods inventory (in months) for stop-fittings. Using the total annual cost of stop-fittings and a 19% inventory holding rate, the finished goods inventory holding cost was estimated as follows:

(16.16 mos ave F/G Inv)($1,384,433 / yr)(1yr / 11 mfg mos)(19% inv holding rate) = $386,433

It should be noted that there are many less tangible costs which may be attributed to inventory, such as lack of responsiveness to customer needs (design changes) and the cost of obsolescence. These have not been accounted for in this analysis.

4.1.3 Total Annual Costs & Average Unit Cost

Total annual cost is simply the sum of the parts cost and the inventory holding costs. This yields:

Total Annual Cost = \$1,384,433 + \$386,433 = \$1,770,866 / yr

Dividing by annual part volume gives an estimate for average unit cost:

Average Unit Cost = (\$1,770,866 / yr) / (9877 units / yr) = \$179.30 / unit

4.2 Cell Produced Stop-fitting Cost

4.2.1 Unit Cost

To determine annual production cost for the stop-fitting cell two components of cost must be considered: material cost and labor cost. Material costs were based on a 6"x4.5"x4" aluminum (7050-T74) forged block or plate stock. The weight of this starting configuration is 10.8 lbs. Using the using the cost per pound of 7050-T74 aluminum in either forged block or plate stock the raw material cost may be simply calculated:

Raw Material Cost = (10.8 lbs / unit)(\$2.00 / lb) = \$21.60 / unit

The next component of cost, labor, is slightly more complicated to calculate. The underlying assumption of labor rate determination is that the cell requires only one operator and that the stop-fittings are batched according to door kits for processing subsequent to the stop-fitting cell. Since labor rates are regarded as proprietary information, neither the following figures nor their ratio are indicative of Boeing's costs. Rather these costs are derived from general industry data and are shown merely for illustrative purposes.

$$\text{Estimated Labor Cost}_{\text{internal}} = \$61.70 \,/\, \text{unit}$$

$$\text{Estimated Labor Cost}_{\text{external}} = \$40.90 \,/\, \text{unit}$$

These costs are intended to represent labor charges from within the cell as well as labor charges from the batch (finishing) operations. Of course, total unit cost also depends upon whether the fitting is produced internally or externally. These costs are simply the sum of labor and raw material costs:

$$\text{Unit Cost}_{\text{internal}} = \$21.60 + \$61.70 = \$83.30$$

$$\text{Unit Cost}_{\text{external}} = \$21.60 + \$40.90 = \$62.50$$

Annual cost estimates are as follows:

$$\text{Annual Cost}_{\text{internal}} = (\$83.30 \,/\, \text{unit})(9877\text{units/yr}) = \$822{,}754$$

$$\text{Annual Cost}_{\text{external}} = (\$62.50 \,/\, \text{unit})(9877\text{units/yr}) = \$617{,}313$$

4.2.2 Inventory Holding Costs

The premise underlying the determination of inventory holding costs under the cellular manufacturing approach to stop-fitting production is that the system will be extremely responsive to demand and require minimal finished goods and WIP inventory. Estimated finished goods inventory is 2 weeks worth. Estimated levels of WIP are 1 week's worth, most of which will be held after the cell, in the batch operations. Using these estimates, current annual volumes and a 19% inventory holding rate, annual holding cost can be determined as follows:

Total Cell Inventory = (2 weeks F/G Inv) + (1 week WIP Inv) = 3 weeks

$$\text{Total Inv Holding Cost}_{\text{internal}} = (3\text{ weeks})(1\text{ mfg yr} / 220\text{ mfg weeks})\ (9877\text{ units} / \text{yr}) \times (\$83.30 / \text{unit})(19\%\text{ inventory holding rate}) = \$2{,}132 / \text{yr}$$

$$\text{Total Inv Holding Cost}_{\text{external}} = (3\text{ weeks})(1\text{ mfg yr} / 220\text{ mfg weeks})\ (9877\text{ units} / \text{yr}) \times (\$62.50 / \text{unit})(19\%\text{ inventory holding rate}) = \$1{,}599 / \text{yr}$$

4.2.3 Total Estimated Cost

The total estimated annual stop-fitting costs are as follows:

$$\text{Estimated Annual Cost}_{\text{internal}} = \text{Annual Cost} + \text{Holding Cost} = \$822{,}754 + \$2{,}132 = \$824{,}886$$
$$\text{Estimated Annual Cost}_{\text{external}} = \text{Annual Cost} + \text{Holding Cost} = \$617{,}313 + \$1{,}599 = \$618{,}912$$

4.3 Cost Savings & Net Present Value

4.3.1 Annual Savings

The total estimated annual savings from the stop-fitting cell differ depending on whether they are sourced internally or externally. The calculations follow:

$$\begin{aligned}\text{Cost Reduction}_{\text{internal}} &= \text{Current Annual Cost - Estimated Annual Cost}\\ &= \$1{,}770{,}866 - \$824{,}886\\ &= \$945{,}980 \,/\, \text{yr}\end{aligned}$$

$$\begin{aligned}\text{Cost Reduction}_{\text{external}} &= \text{Current Annual Cost - Estimated Annual Cost}\\ &= \$1{,}770{,}866 - \$618{,}912\\ &= \$1{,}151{,}954 \,/\, \text{yr}\end{aligned}$$

On a percentage basis the annual cost savings are as follows:

$$\text{Percentage Savings}_{\text{internal}} = (\$945{,}980 \,/\, \$1{,}770{,}866)(100\%) = 53.4\ \%$$
$$\text{Percentage Savings}_{\text{external}} = (\$1{,}151{,}954 \,/\, \$1{,}770{,}866)(100\%) = 65.1\ \%$$

4.3.2 Initial Investment

Table 4.1 provides an itemized list of all the initial non-recurring expenditures associated with the implementation of the stop-fitting cell. The difference between internal cost and external cost is a reflection on differing labor rates between external suppliers and BCAG.

Equipment / Engineering Expense	Internal Cost	External Cost
(1) 5-axis CNC Machining Center	$770,000	$770,000
(1) Hardness Tester	$5,000	$5,000
(1) Electrical Conductivity Tester	$5,000	$5,000
(1) 3-axis Milling Machine	$40,000	$40,000
(2) Ardrox Processing Carousels	$100,000	$100,000
(1) Vibratory Deburr Drum	$15,000	$15,000
(1) Shot Peen Booth	$15,000	$15,000
(1) Coordinate Measuring Machine	$150,000	$150,000
(50) Drawing Changes	$146,300	$146,300
(108) NC Programs	$488,400	$130,400
Total Non-recurring Costs	$1,734,700	$1,376,700

Table 4.1 Itemized Non-recurring Stop-fitting Cell Expenditures

4.3.3 Net Present Value

The total non-recurring investment can be coupled with the annual savings to determine the net present value of the investment in the proposed stop-fitting cell. Several rather conservative assumptions were made for the NPV calculation: (1) the cell life is assumed to be ten years, (2) the residual value of the cell equipment is assumed to be negligible, (3) maintenance and utilities costs for the cell are assumed to be approximately equal to current costs (therefore net savings are negligible), (4) the discount rate is assumed to be equal to 11.3%. The NPV's for both an internal and an external cell are shown below. Appendix B shows the detail NPV analysis.

$$\text{NPV}_{\text{internal}} = \$1.820\text{ M}$$
$$\text{NPV}_{\text{external}} = \$2.923\text{ M}$$

Note that this NPV calculation is a rough estimate. Since all assumptions are conservative and the results are strongly positive, the value of a more comprehensive analysis is limited.

Chapter 5: Conclusion

5.1 Review of Findings

5.1.1 Cellular Manufacturing Applicable to Low-volumes

The traditional theory of manufacturing layout is outdated. No longer is a product layout economical for only high-volume production. The high level of flexibility which today's machine tools are capable of makes the application of cellular manufacturing to low-volume production an extremely attractive option.

Two key principles can be applied to generate the volumes necessary to make cellular manufacturing cost effective. First, introduce as much commonality into a group or family of parts as is practical. Secondly, design manufacturing cells with enough flexibility to accommodate those differences which exist between parts in a part-family.

Ideally, commonality is pursued in the initial design phase of a product, but it can be introduced to mature products through redesign. Redesigns may be modest or quite extensive. The primary factor to be considered when redesigning for commonality is processing. In other words, parts should be redesigned so that to the manufacturing system they "look" very similar. This may entail changes to geometry, materials, or both. Making parts look very similar to the manufacturing system effectively increases the volume of product which may be processed through a particular cell and allows economies of scale to be realized.

Flexibility broadens a particular cell's definition of "very similar." The goal of introducing flexibility is to allow the manufacturing cell to accommodate the variation between parts in a part-family. Increased levels of flexibility will increase the number of parts which look very similar to the cell, thereby effectively increasing the volume of parts which may be processed. Flexibility allows a cell to process a wider range of parts, thus generating economies of scope.

It is important to note that greater levels of commonality require less flexibility and lesser levels of commonality require more flexibility. In this way, these two keys to cellular manufacturing can be "traded-off" to find the most economical mix of commonality and flexibility. This mix will differ for each part-family under consideration and currently there is no precise way to determine the best ratio. A methodology to find this ratio would be an interesting area for further research.

5.1.2 Substantial Savings Can be Realized

The cost savings which can be realized by moving from a process layout to a product layout are in excess of 50%. The stop-fitting case study showed an estimated 53-65% savings for internally produced and purchased parts, respectively. While on the surface this seems to be a very aggressive target, in reality it is quite conservative. The majority of the savings realized in this case-study stem from labor savings, however, reductions in labor expense are just the beginning.

Improvements due to cellular manufacturing go well beyond those which are easily quantifiable. Moving to a cellular mode of manufacturing joins fragmented operations into a unified whole. This unified process eliminates linkages between operations, thereby decreasing cycle-time and in-process inventory. It also allows operators to see the entire process, creating greater process knowledge, improved quality, increased morale, and greater employee satisfaction. Smaller batch sizes reduce in-process inventory and allow the manufacturing system to respond more quickly to demand (via decreased lead-times), thereby reducing finished goods inventory. Low levels of finished goods inventory make design changes more affordable (through decreased inventory obsolescence), thereby increasing their likelihood and, ultimately, customer satisfaction. The list of cellular manufacturing's benefits goes on. Since these gains are difficult to quantify, they have not been included, and this analysis has been allowed to stand primarily on the basis of its labor savings. The many significant, yet difficult to quantify, benefits of cellular manufacturing make it even more attractive than these projections suggest.

5.1.3 Cellular Manufacturing is Widely Applicable

Cellular manufacturing may be applied to most detail part fabrication. The stop-fitting cell is not an isolated example. In fact, many opportunities to form part-families and manufacturing cells exist throughout BCAG and at other low-volume manufacturers. The reality is that the current manufacturing strategy has, to a large extent, hidden these opportunities from view.

In order to ensure the success and growth of cellular manufacturing, several pilot cells (such as the stop-fitting cell) must be implemented and made visible throughout the organization. The concept of cellular manufacturing is not a difficult one. However, it is foreign to the aerospace industry. Having a working example in operation will greatly facilitate widespread adoption.

5.1.4 Management Must Remove Barriers

Currently, existing long-term contracts present the most serious barrier to cellular manufacturing. Today, parts which would comprise a part-family are spread among tens of suppliers. Grouping parts into a family for production at one supplier would entail breaking a large number of contracts. However, this is exactly what must happen if the benefits of cellular manufacturing are ever to be realized. It must be recognized that the current purchasing strategy is based on optimization at the part level and makes no attempt to take advantage of economies of scope or scale. Optimization at the part-family level will allow BCAG to realize these economies.

Lastly, responsibility centers (and specifically responsibility center managers) must be given a span of control broad enough to effect the change necessary to implement cellular manufacturing. This means that the product center manager must have direct control over the product definition, purchasing, material management, and facilities functions at a minimum. It is unreasonable to mandate significant cost reductions without giving responsibility centers direct control over the disciplines necessary to achieve these goals.

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Appendix A: Equipment Specifications

Table A1 lists the equipment necessary to construct the stop-fitting cell along with cost estimates. This appendix will discuss equipment specifications in greater detail and provide a justification for specific selections.

Equipment	Cost
(1) 5-axis CNC Machining Center	$770,000
(1) Hardeness Tester	$5,000
(1) Electrical Conductivity Tester	$5,000
(1) 3-axis Milling Machine	$40,000
(2) Ardrox Processing Carousels	$100,000
(1) Vibratory Deburr Drum	$15,000
(1) Shot Peen Booth	$15,000
(1) Coordinate Measuring Machine	$150,000
Total Equipment Costs	$1,100,000

Table A1 Cell Equipment and Costs

5-Axis Machining Center

The many different geometries which must be accommodated by this machine necessitate 5 axes. While a 4-axis machine would accommodate a majority of parts, there are several major drawbacks: (1) specialized cutting tools are required to compensate for the lack of a 5th axis, (2) a larger tool carousel will be required to hold the specialized tooling, (3) tooling management becomes more complex, (4) processing time increases since the most efficient cutter paths are not accessible, and (5) the entire part-family cannot be machined in the cell. These concerns constitute a strong case for a 5-axis machining center.

In order to accommodate all the tooling necessary to machine the entire part-family it is advisable to purchase a large tool carousel. The carousel allows the machine to hold all the tools necessary to machine all parts. This eliminates the need to change tools when setting up a new part and significantly decreases set-up time.

A tool monitoring / probing system is also required. This system will ensure that the NC programs use the correct tool offsets automatically.

A high speed spindle is required to decrease processing time at the machining center so that it falls within the required cell cycle-time without adding an additional machining center.

A machine controller with sufficient memory told all the NC programs necessary to machine all parts in the family is required. This eliminates the need to upload NC programs at each set-up and, therefore, reduces set-up time.

A 5-axis machining center which meets these specifications was identified. The machine (a Mazatech H-630 5X) and its cost breakdown are shown in Table A2.

Mazatech H-630 5X	**Cost**
Base price	$559,300
15,000 rpm spindle	$57,400
120 tool chain-type magazine	$52,200
Chip conveyor	$7,000
Boeing specified paint	$1,500
Foundation	$60,000
Spindle cleaning tool	$6,600
Tool-shank cleaner	$2,100
Tool monitor / probe	$4,300
25,000 blocks of controller memory	$16,300
Total	$766,700

Table A2 Machining Center Specifications and Cost

Hardness Tester

A standard, manually operated hardness tester is sufficient for this operation.

Electrical Conductivity Tester

A standard conductivity tester is sufficient for this operation.

3-Axis Milling Machine

A standard Bridgeport-type milling machine with a small controller is sufficient for this operation.

Ardrox Processing Carousels

Ardrox processing carousels are self-contained units which allow automated, sequential processing of parts at up to five different stations. These units can be used to prepare the stop-fittings for fluorescent penetrant inspection as well as for etching.

Vibratory Deburr Drum

A standard vibratory bowl / drum with finishing media can be used to process stop-fittings at this operation.

Shot-peen Booth

A manually operated shot-peen booth with a cabinet larger than 2'x2'x2' is sufficient to perform this operation.

Coordinate Measuring Machine

A rather unsophisticated coordinate measuring machine (CMM) will suffice for this operation. The CMM must be able to handle parts falling within a 1' cube (allows for tooling) and must have sufficient memory to store inspection programs for all parts in the family. Accuracy of the CMM should be at least +/- .001 inches.

Appendix B: NPV Analysis

Assumptions

- Ten year cell life
- Residual value of equipment at ten years is negligible
- Maintenance and utilities savings are negligible
- Analysis is on cost savings basis
- All figures in real terms

Discount Rate Determination (in real terms)

DR = (risk free rate - inflation rate) + β_{Boeing}(Average Market Risk Premium)
DR = (7% - 4%) + 1.04(8%) = 11.32%

NPV Analyses

Produced	Internally										
Real discount rate (%)	11.32										
Project Life (yrs)	10.00										
Tax Rate (%)	34.00										
Period	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Non-recurring Exp											
Capital Equip	1100.00										
Engr Effort	146.30										
N/C Programming	488.40										
Total Non-recurring	-1734.70										
Real Annual Savings		945.98	945.98	945.98	945.98	945.98	945.98	945.98	945.98	945.98	945.98
Depreciation Tax Shield		37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40
Sub total		983.38	983.38	983.38	983.38	983.38	983.38	983.38	983.38	983.38	983.38
Income Tax		-334.35	-334.35	-334.35	-334.35	-334.35	-334.35	-334.35	-334.35	-334.35	-334.35
Net Cash Flow	-1734.70	575.56	510.41	452.63	401.39	355.95	315.66	279.93	248.24	220.14	195.22
Net Present Value	$1,820.43										

Table B1 NPV Analysis for Internally Located Cell

Produced	Externally										
Real interest rate (%)	11.32										
Project Life (yrs)	10.00										
Tax Rate (%)	34.00										
Period	0.00	1.00	2.00	3.00	4.00	5.00	6.00	7.00	8.00	9.00	10.00
Non-recurring Exp											
Capital Equip	1100.00										
Engr Effort	146.30										
N/C Programming	130.40										
Total Non-recurring	-1376.70										
Real Annual Savings		1151.95	1151.95	1151.95	1151.95	1151.95	1151.95	1151.95	1151.95	1151.95	1151.95
Depreciation Tax Shield		37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40	37.40
Sub total		1189.35	1189.35	1189.35	1189.35	1189.35	1189.35	1189.35	1189.35	1189.35	1189.35
Income Tax		-404.38	-404.38	-404.38	-404.38	-404.38	-404.38	-404.38	-404.38	-404.38	-404.38
Net Cash Flow	-1376.70	696.11	617.31	547.43	485.46	430.51	381.78	338.56	300.23	266.25	236.11
Net Present Value	$2,923.07										

Table B2 NPV Analysis for Externally Located Cell maximum dimension of 150" (roughly the diameter of a 757 fuselage section), 1:250,000 translates to 0.0006".

- Film warpage could skew measurements.
- Lense distortion due to temperature or other environmental factors could skew measurements.
- Rounding error in the bundle adjustments could cause inaccuracy.

- scale bar: certified to 0.0005" for a 111" bar
  - The accuracy of the entire survey can only be as accurate as the scale bar.
  - Many advocate the use of multiple scale bars. This allows weighting for potential errors and gives option of not using a scale bar that is obviously incorrect. For example, some scale bars require insertion of retroreflective targets at the ends. If these targets are not correctly inserted, the length of the scale bar will be different than its calibrated length.
  - It would be ideal to have the scale bar be at least as long as the max dimension of the structure. This way any error in the scale bar will not multiply as the scale is extrapolated to far-reaching points.
  - If multiple scales are used, the bundle adjustment program tries to best fit all the scale bars to their specified value.
  - It is very important to have good geometry on the scale bars. The scale bars are going to define the dimensions of the entire structure, therefore, it is essential that the error on the scale bar coordinates be very low.
  - If invar scale bars (zero coeff of thermal expansion) are used, the shape of the structure can be determined at a given temperature. It is very important that the temperature be taken during surveys using invar scale bars. Otherwise, the data is meaningless because we have no idea what the structure may be doing at any other temperature.
  - If a like material scale bar is used, it will expand (theoretically) as much as the structure. Therefore, the shape of the structure can be determined at any temperature.
  - The object to be measured and scale bars should have equilibrated to temperature before taking photographs.
  - Because the picture taking process in photogrammetry takes a relatively short period of time, shape change due to temperature change during the shoot is minimized. The part will not be undergoing deformation as measurements take

place. This is not necessarily true for other measurement methods such as computer-aided theodolites.

- environmental/human factor: Results from the accuracy experiment show that the variability introduced by environmental factors/human error is 0.0013" (1σ).
  - Inconsistencies in targeting, including target placement on structure and target placement in the bushing, will result from human error and environmental imperfections (e.g. dust particles).

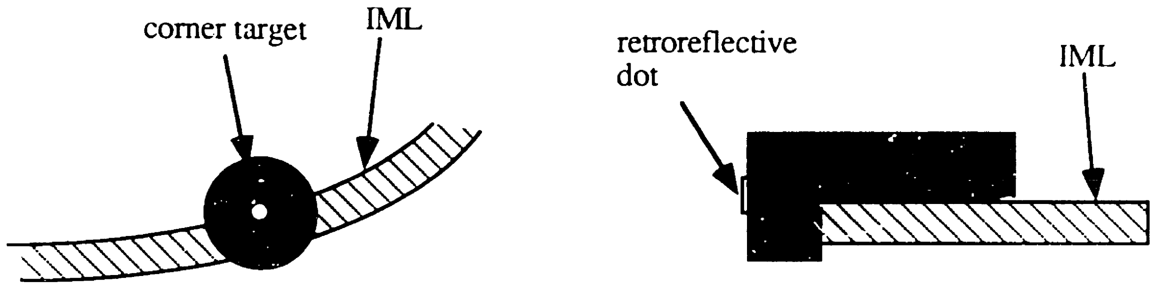
Appendix B: Experimental Procedure and Results for Photogrammetry Repeatability Experiment

Purpose

The purpose of this experiment was to determine the repeatability of the photogrammetry measurement process when applied in the production environment. The airplane characteristic studied in the pilot project in Section 3 was the inner mold line (IML) contour, therefore the repeatability experiment was performed by repeatedly measuring this characteristic. The IML contour of the 41 section was surveyed three times. The first survey was the regular survey. The second and third surveys were subsets of the first

Experimental Setup and Procedure

Survey 1: 62 corner targets (see Figure B.1) were placed, evenly spaced, around the IML contour. 8 seat track studs were targeted and used as control points. Placed scale bars so that they could be seen by second and third survey camera positions. Take pictures from predetermined camera positions.



FRONT VIEW

SIDE VIEW

Figure B.1: Configuration of a Corner Target

Survey 2: Without disturbing the targeting, another set of pictures were taken from the same camera positions as Survey 1.

Survey 3: Seat track targets/bushings were removed. The labels were not removed; they remained the same as Surveys 1&2. The seat tracks were retargeted. No effort in excess of normal targeting procedures was exerted to reproduce the targeting in Surveys 1&2.

This more effectively simulates the variability from survey to survey of the measurement process. Pictures were taken from the same camera positions as Surveys 1&2.

Analysis: 1) Read film from Survey 1. Used the seat tracks as control points.

2) Read film from Survey 2. Used the seat tracks as control points.

3) Read film from Survey 3. Used the seat tracks as control points.

4) Performed analysis to determine variability of IML targets from survey to survey. Repeatability is influenced by the targeting process and the picture taking process (includes film measurement and bundle reduction). The components of these two processes which could be contributing to repeatability variability are listed below.

targeting process	picture taking process
• target variability • bushing variability • human error • environment, e.g. dirt, vibration • warping of structure due to human weight during targeting.	• camera positioning variability • film warping or contamination • round-off error in software • environment - mainly temperature changes

In comparing Surveys 1&2, none of the targeting was changed, therefore, the comparison reflects only the effect of the picture taking process. In comparing Surveys 1&3 and Surveys 2&3, the effect of the targeting process is partly captured. It would have been ideal to retarget the IML targets, as well as the seat track targets, however, due to time and precision limitations, it was not feasible to do this.

	compare S1 and S2 $\sqrt{(x1-x2)^2+(y1-y2)^2+(z1-z2)^2}$	compare S2 and S3 $\sqrt{(x2-x3)^2+(y2-y3)^2+(z2-z3)^2}$	compare S1 and S3 $\sqrt{(x1-x3)^2+(y1-y3)^2+(z1-z3)^2}$
seat track targets	• picture taking • $\bar{x}=0.0029$ • $\sigma=0.0018$	• picture taking • seat track targeting • $\bar{x}=0.0073$ • $\sigma=0.0026$	• picture taking • seat track targeting • $\bar{x}=0.0067$ • $\sigma=0.0031$
IML targets	• picture taking • $\bar{x}=0.0069$ • $\sigma=0.0029$	• picture taking • seat track targeting • $\bar{x}=0.0067$ • $\sigma=0.0022$	• picture taking • seat track targeting • $\bar{x}=0.0107$ • $\sigma=0.0049$

Each survey consisted of 60 IML target locations. The targets locations in Survey i are $[p_{i1}=(x_{i1},y_{i1},z_{i1}), p_{i2}=(x_{i2},y_{i2},z_{i2}),\ldots,p_{i62}=(x_{i62},y_{i62},z_{i62})]$, where i=1,2,3.

The differences between the results of the three surveys were treated as treatments in an analysis of variance (see Table B.1). It seems that treatments B and C should be the same since they are both testing for the same elements of repeatability. However, the results show that treatments A and C are the same (see Table B.2). This seems to suggest that the process of seat track targeting does not affect the repeatability of the photogrammetry process; however, then treatments A and B should also be the same. This is not the case.

Given the significantly contradictory results, it is unclear how the picture taking process and seat track targeting process affect the repeatability of the photogrammetry process. However, the grand mean of treatments A, B, and C is 0.00810". This grand mean can be used as an approximation of the repeatability of the photogrammetry process.

Table B.1

treatment	surveys compared	elements of photogrammetry process repeatability	mean [in]	std dev [in]	RMS [in]
A	1&2	• picture taking	0.0069	0.0029	0.0028
B	1&3	• picture taking • seat track targeting	0.0107	0.0049	0.0050
C	2&3	• picture taking • seat track targeting	0.0067	0.0022	0.0022

Table B.2

AB					
source	df	SS	MS	F	prob
treatment	1	0.000440	0.000440	27.1	0.0000
error	118	0.00191	0.000016		
total	119	0.002350			
AC					
source	df	SS	MS	F	prob
treatment	1	0.000001	0.000001	0.171	0.681
error	118	0.000775	0.000007		
total	119	0.000776			
BC					
source	df	SS	MS	F	prob
treatment	1	0.000485	0.000485	33.1	0.0000
error	118	0.001732	0.000015		
total	119	0.002217			

Appendix C: Calculation of Thermal Expansion of Skin Panels

Coefficient of thermal expansion for aluminium: 24/MK or 1.3e10-5/°F.

expansion = (temp diff)•(coeff of thermal exp)•(typical length of skin panel = 45")

month	avg. temp. Sea-Tac [°F]	avg. temp. Wichita [°F]	difference: Sea-Tac - Wichita [°F]	expansion (+) or contraction (-) [in]
January	•	•	•	•
February	•	•	•	•
March	•	•	•	•
April	48.4	56.4	-8.0	-0.0047
May	55.1	65.4	-10.3	-0.0060
June	60.1	75.3	-15.2	-0.0089
July	64.5	80.3	-15.8	-0.0092
August	64.0	79.4	-15.4	-0.0090
September	59.6	71.0	-11.4	-0.0067
October	51.9	59.5	-7.6	-0.0044
November	44.6	45.1	-0.5	-0.0003
December	•	•	•	•

Note: These are typical monthly temperatures obtained from the weather almanac.

For the months during the 41/43 project (May, June, July, August, September, October, November, December, and January), the average contraction is: 0.0063", the standard deviation is: 0.0032". Assume that the contractions during these months are N(-0.0063, 0.0032). For the months of December to March, both factories were heated to the same temperature indoors, therefore, there was no expansion due to temperature difference during these months.

Appendix D: Calculation of Area Difference for Circumference Change

To simplify calculations, the cross section of the 43 section was assumed to be circular with a circumference of 483.571 in. This is the actual length of the IML curve; however, the curve is actually a combination of circular sections and parabolic sections.

C_0 = engineering defined circumference of 43 section = $2\pi r_0$ = 483.571 in
a_0 = engineering defined area of 43 section = πr_0^2

$$r=\frac{C}{2\pi} \tag{D-1}$$

$$\begin{aligned} a&=\pi r^2 \\ &=\frac{C^2}{4\pi} \end{aligned} \tag{D-2}$$

The difference between the engineering defined area and an area with a different radius is:

$$a-a_0=\frac{C^2-C_0^2}{4\pi} \tag{D-3}$$

The distribution of the 43 section circumference deviations is N(-0.0063in, 0.035in^2) (see Section 3.3.2). Characteristics of the area difference distribution are shown in Table D.1

Table D.1: Distribution of area difference due to circumference change for the 757 43 section

expected values calculated from tolerance buildup	**C [in]**	**$a-a_0$ [in]**
expected mean	C_0-0.0063	-0.4849
expected +3σ	C_0-0.0063+3(0.035)	7.5970
expected -3σ	C_0-0.0063-3(0.035)	-8.5650

To calculate the area differences between engineering and actual cross sections, the circumference of the cross section was approximated by fitting a curve through the measured target points on the IML. Using equation D-3, the area differences were calculated. The results are displayed in Table D.2.

Table D.2: Area differences due to circumference change for the 757 43 section

airplane number	C_{circ} [in]	a_{circ}-a_0 [in^2]
2	483.5529	-1.3930
3	483.6572	6.6348
5	483.6843	8.7209
6	483.5209	-3.8556
7	483.5167	-4.1788
8	483.4738	-7.4800
9	483.5435	-2.1164
10	483.6989	9.8448
11	483.6576	6.6656
13	483.6179	3.6113
15	483.6249	4.1455
16	483.6511	6.1652
17	483.7193	11.4138
18	483.5957	1.8995
20	483.7573	14.3417

Appendix E: Calculation of Area Difference for Deformation

To determine the area difference due to deformation, the total area difference between the actual IML and the engineering defined IML was calculated. Then the area difference due to circumference change was subtracted from this value; the remainder represents the area difference due to deformation. To calculate the total area difference, area differences due to each IML deviation were averaged. Each IML deviation was treated as a radius change of the cross section, Δr. The area corresponding to the new radius, a_i, was then calculated. The engineering defined area, a_0, was then subtracted from a_i to determine the area difference, Δa_i. To determine the total area difference for the entire section, all the Δa_i's were averaged. area $\text{diff}_{\text{circ}}$ was subtracted from this to give area $\text{diff}_{\text{deform}}$.

r_0 = engineering defined radius of 43 section = 76.9627 in
C_0 = engineering defined circumference of 43 section = $2\pi r_0$ = 483.571 in
a_0 = engineering defined area of 43 section = πr_0^2

$$a_i = \pi r_i^2 \tag{E-1}$$

$$\Delta a_i = |a_i - a_0| \tag{E-2}$$

$$\text{total area difference} = \frac{\sum_{i}^{\text{entire section}} \Delta a_i}{\text{number of IML measurements around section}} \tag{E-3}$$

$$\text{area diff}_{\text{deform}} = \text{total area difference} - \text{area diff}_{\text{circ}} \tag{E-4}$$

The control limits for area difference due to deformation are [0, 15.4775in^2].

Table E.1: Area differences due to deformation for 757 43 section

airplane number	total area difference	area $\text{diff}_{\text{circ}}$	area $\text{diff}_{\text{deform}}$
2	24.2414	1.3930	22.8484
3	35.7564	6.6348	29.1216
5	32.7798	8.7209	24.0589
6	23.5138	3.8556	19.6582
7	78.7363	4.1788	74.5575
8	32.2527	7.4800	24.7727
9	33.1612	2.1164	31.0448

10	26.2478	9.8448	16.4030
11	20.6984	6.6656	14.0328
13	24.1473	3.6113	20.5360
15	25.4017	4.1455	21.2562
16	44.9702	6.1652	38.8050
17	30.8890	11.4138	19.4752
18	25.0914	1.8995	23.1919
20	68.8593	14.3417	54.5176