The Cost of Variation and a Process to Reduce Variation in the Assembly of Mature Aircraft Designs

by

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S.B., Materials Science and Engineering, Massachusetts Institute of Technology (1987)

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Abstract

The quality and the price of a product are two of the main sources of competitive advantage. These in turn are very dependent upon the production processes used to produce the product. Variation in the production process is a major source of waste, rework, non-value-added costs, and lowered quality.

The Boeing Company is the world's leading manufacturer of Commercial jet aircraft. However, this industry is fiercely competitive, and Boeing will not be able to rest upon its past laurels. As the cornerstone of Boeing's strategy to maintain its premier position, the company has committed itself to the continuous improvement of its products and processes. Reducing and controlling variation in the production process would greatly contribute to Boeing's goal of cutting waste, lowering costs, and boosting quality.

This thesis documents the author's findings as a result of a six month internship at The Boeing Company in the Door Responsibility Center. The following are provided:

- A discussion of the effects of variation on production costs and product quality
- A discussion of Boeing's process to reduce and manage variation on new designs through the use of key characteristics, as well as the limitations of applying this process to older designs
- An estimate of the costs of variation based on a case study of shimming and trimming the 757 # 4 Passenger Door
- A proposed method for reducing and controlling variation in the assembly of mature products

Variation in the production process results in rework, which currently accounts for approximately 40% of the direct labor to build an airplane. In the Door Responsibility Center, the estimated annual cost of shimming and trimming alone is $1.19 million, and these operations account for only a small portion of the rework resulting from variation in the parts and the assembly process. The use of key characteristics alone will not solve the variation related production problems. To correct these problems, an in-depth investigation of the design, the detail parts and assemblies as-produced, the manufacturing plan, and the tool indexing plan is required in addition to the identification and measurement of key characteristics.

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Chapter 1: Introduction

The Boeing Company is the world's leading manufacturer of commercial aircraft. However, the commercial aircraft industry is an intensely competitive environment, and Boeing will not be able to rest upon its past laurels. The current market for commercial aircraft has been weakened by several years of depressed business for the airlines, resulting in declining orders for aircraft. Along with this, Boeing faces tough competition from Airbus. Airbus has been steadily gaining market share over the past fifteen years by introducing very competitive products.

In this industry, two of the main sources of competitive advantage are the quality and the price of the product. Quality and price are very dependent upon production processes. As the cornerstone of Boeing's business strategy to maintain its premier position, the company has committed itself to continuous improvement of its products and processes.[1] Boeing's goal is to cut waste and boost productivity, achieving higher quality products at the lowest possible costs. Variation in the production process is a major source of waste, rework, non-value-added costs, and lowered quality. Reducing and controlling variation in the production process would greatly contribute to Boeing's goal of cutting waste, lowering costs, and boosting quality.

This thesis documents the author's findings as a result of a six month internship at The Boeing Company in the Renton Door Responsibility Center. The document provides the following:

- An examination of the effects of variation on production costs and product quality
- A discussion of Boeing's process to reduce and manage variation on new designs, as well as the limitations of applying this process to older designs

[1] *The Boeing Company 1993 Annual Report*, 4.

- An estimate of the costs of variation based on a case study of shimming and trimming the 757 # 4 Passenger Door
- A proposed method for reducing and controlling variation in the assembly of mature products

Thesis Outline

Chapter Two examines the sources of variation and its effects on the assembly process. In addition, a Boeing-developed process for managing variation on new aircraft design is presented. Finally, the limitations of this process with respect to applying it to aircraft already in production are discussed.

Chapter Three presents a case study of the Boeing Door Responsibility Center, highlighting some of the costs arising from variation. This provides the motivation for implementing a process to reduce and control variation. In particular, some of the costs of rework resulting from variation in the build process of the 757 #4 Passenger Door are presented. The cost implications of this rework, both in terms of Boeing production and customer operations, are discussed.

A method for reducing and controlling variation in the assembly of mature aircraft designs is presented in Chapter Four. This proposed process provides a targeted approach for applying limited resources to achieve the greatest reduction of rework costs and flow time.

Chapter 2: Variation in the Assembly Process

Variation arising in the production of any product disrupts the production process, drives up production costs, and adversely impacts the finished product quality. Reducing and managing variation inherent in the various aspects of the production process are key to reducing production costs and increasing product quality. Sources and effects of variation in the assembly process of aircraft are presented below, along with Boeing's approach on new designs to alleviate variation and its associated costs. Finally, limitations of this approach as applied to mature aircraft designs are discussed.

2.1 Assembly Problems Result From Variation

Variation enters the assembly process in several forms. The most notable result is that parts do not fit together as intended. Unscheduled rework is then required to complete the production process. The impacts of variation run much deeper than the added labor time and material costs of rework. This section presents the major causes of assembly problems at Boeing and the impacts these problems have had on the company.

Variation causes assembly problems throughout the production process. Parts do not fit together as intended as a result of variation in the four components of production: the engineering design, the detail part dimensions, the tooling or tool-indexing, and the manufacturing process. Typical sources of variation in these areas are shown in the cause and effect diagram in Figure 2.1.1[2].

Boeing's existing products, the 737, 747, 757, and 767, were designed between 14 and 30 years ago, before computer-aided-design and digital definition were feasible technologies. The planes were drawn by hand, from the detail level up to the top installation level. This process allowed for many errors, from inadequate definition to

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[2] Adapted from Dari Shalon, *Indexed Pre-Assembly with Variations; A Method of Representing Variations of Parts and Tools in CATIA*. (MIT Mater's Thesis, 1992) 8.

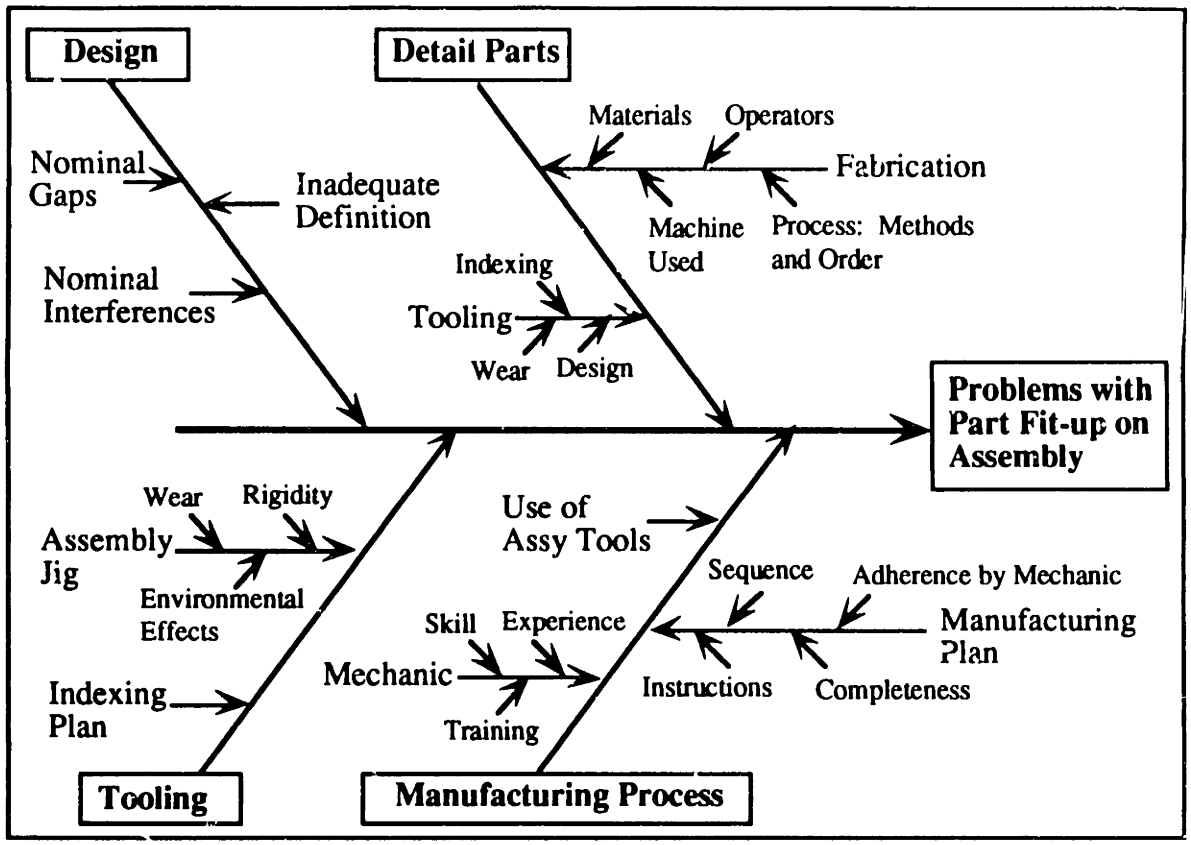

Figure 2.1.1: Cause and Effect Diagram of Sources of Assembly Problems

uncoordinated mating surfaces to unintentionally designed-in interferences and gaps. Of the most interest for this discussion is the practice of applying tolerances.

The design typically accommodates some inherent variation in detail parts with the definition of tolerances, which indicate those locations where controlling variation is more or less critical. However, the tolerances dictated for sheet metal structure, which constitutes the majority of the airplane, are typically +/- 0.03 inches for details, assemblies and installations. This inadequate dimensioning and tolerancing allow nominal gaps and interference conditions at the assembly and installation levels even when detail parts are made within the tolerance specifications. Adding to this the common occurrence of detail part variation leads to too many occasions where assembly problems can and will arise.

The most notable effect of variation on the assembly process is the need for rework and its added costs to production. Rework is an unplanned portion of production. At Boeing, rework is estimated to account for approximately 35-[illegible]0% of the direct labor required to build an airplane. Rework consists of activities such as shimming, trimming, pulling holes[3], oversizing holes, hand-forming parts at assembly, disassembling and re-assembling some sub-assemblies with replacement parts to alter dimensions, and fabricating one-of-a-kind parts to replace a part that cannot be altered to fit.

Variation also affects product quality. While Boeing takes the necessary steps to insure that rework restores parts and assemblies to the design intent, the quality of the airplane is still affected. For example, the airplane weighs more, influencing the customer's operating costs. Also, the use of over-sized fasteners in an area limits the customer's ability to make repairs to that area. The customer perceives that the quality of the product has deteriorated as a result of rework, and the argument that the airplane still meets or exceeds the design intent will not change this perception.

Another notable though easily overlooked effect of variation is deteriorating employee morale. Morale falls when employees have to deal daily with parts that do not fit. Employees blame each other, out of frustration, for the problems they face. As examples: mechanics blame the engineers for design errors or they blame tooling for inadequate or faulty tooling; mechanics blame personnel in upstream production stages for building in the problems; and engineers blame mechanics for improperly using the tools or not following the manufacturing plan.

Variation has a far-reaching affect on the production process and product quality. The most notable result is the need for rework. Rework adds considerable cost and flow time to the production process. Rework has much greater implications, however, than the

---

[3] Variation creates conditions where pre-drilled pilot holes cannot be used to locate the fastener, either due to short-edge-margin or interference conditions. The fastener location is adjusted by drilling off center with the pilot hole; this is called pulling the hole.

cost of the added direct labor and the added production time. These implications are further explored in the next section.

2.2 The Costs of Variation in the Production System

The affects of variation on production run much deeper than obvious costs of rework such as additional direct labor, added production flow time, and scrap and replacement materials. While these costs are significant, the hidden costs grossly exceed them. The hidden costs, shown in Figure 2.2.1, arise from the support structure within Boeing that has evolved over the past thirty years to handle rework.

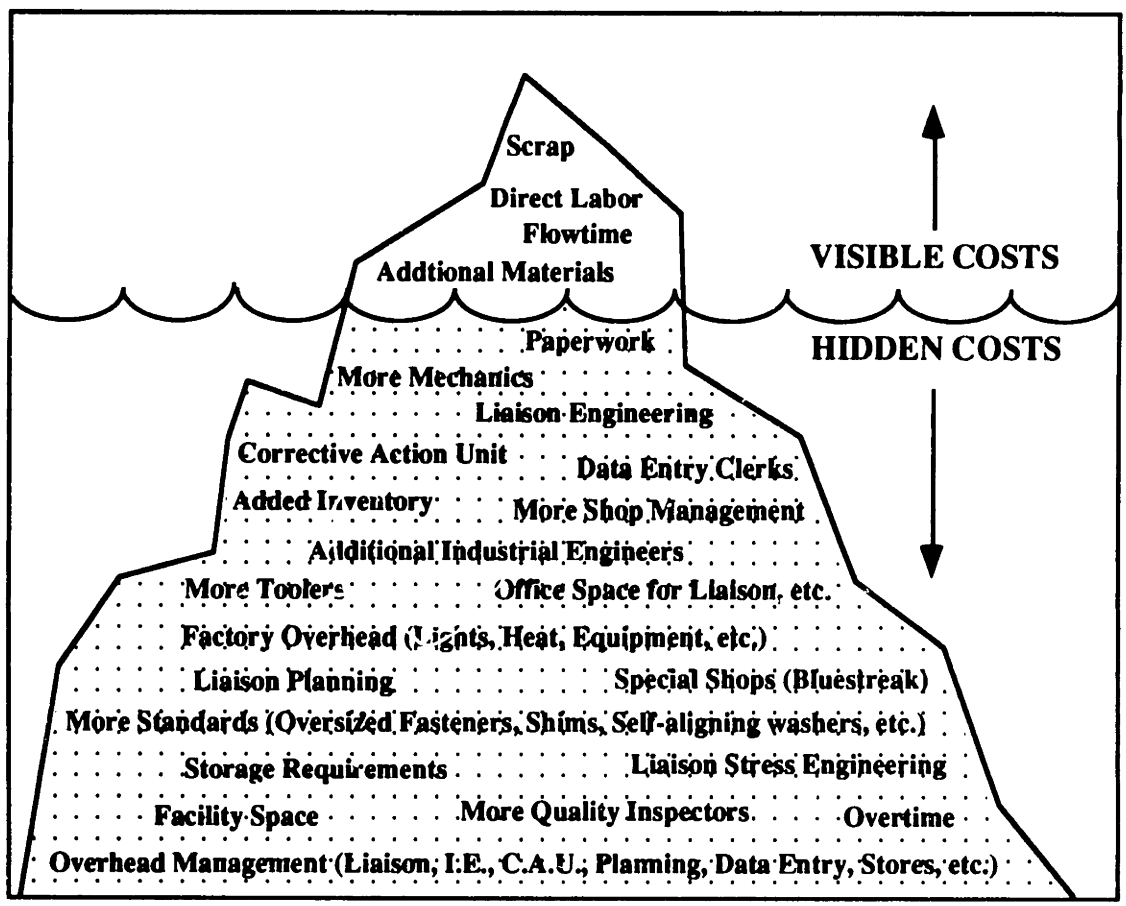

Figure 2.2.1: Hidden Costs of Rework

The support structure and its associated costs are a result of the system dynamics in Boeing's production environment. Production is schedule driven. When problem

symptoms arise, the production schedule does not provide sufficient time to search for the root cause. The system requires an immediate fix to alleviate the symptom, and more importantly, maintain the schedule.

To maintain product quality and accountability to the Federal Aviation Administration, liaison engineers dictate the rework procedures required to restore the parts to their original design intent. Quality assurance inspectors verify that the rework is performed according to engineering's instructions. Liaison planners are needed to create the manufacturing plans for accomplishing the rework dictated by liaison engineers. Additional industrial engineers are needed to adjust the shop schedule to account for the variable amount of direct labor required to complete a job due to the variable amount of rework occurring in each job . Furthermore, people are needed to process and track all of the paperwork associated with this rework.

Without an understanding of the root causes, appropriate action is not taken to prevent further occurrences of a given problem. Corrective action organizations are formed to investigate the problems documented on the rework paperwork. However, the production personnel who have the best understanding of the problem are not included in the investigation; they are too busy trying to maintain the production schedule. As a result, support functions removed from the factory floor are responsible for trying to uncover the cause of the problems.

The root causes most often are not uncovered, or perhaps they are ignored in some circumstances, and the problems worsen over time. At some point the problem can no longer be ignored because of the delays it causes in production or the growing overhead costs associated with dispositioning and documenting the rework. By this time, the problem has become extremely complicated. Finding the root cause and implementing a permanent solution becomes a monumental task, both in terms of time and resources. Rather than committing the resources to undertake such a large task, the short-term rework becomes institutionalized as part of normal production.

This system response is not unique to Boeing. Peter Senge labels this phenomena of short-term improvements leading to long-term dependency as "Shifting the Burden."[4] This concept is illustrated by the causal loop diagram in Figure 2.2.2 At Boeing, it is a vicious cycle that perpetuates the need for rework and increases the size of the non-value-added bureaucracy required to handle rework. The leverage point for breaking the cycle is to identify and implement fundamental solutions rather than quick fixes. In this case, the fundamental solution requires focusing attention on the assembly process and aligning the efforts of the engineering, manufacturing planning and tooling functions to the assembly process.

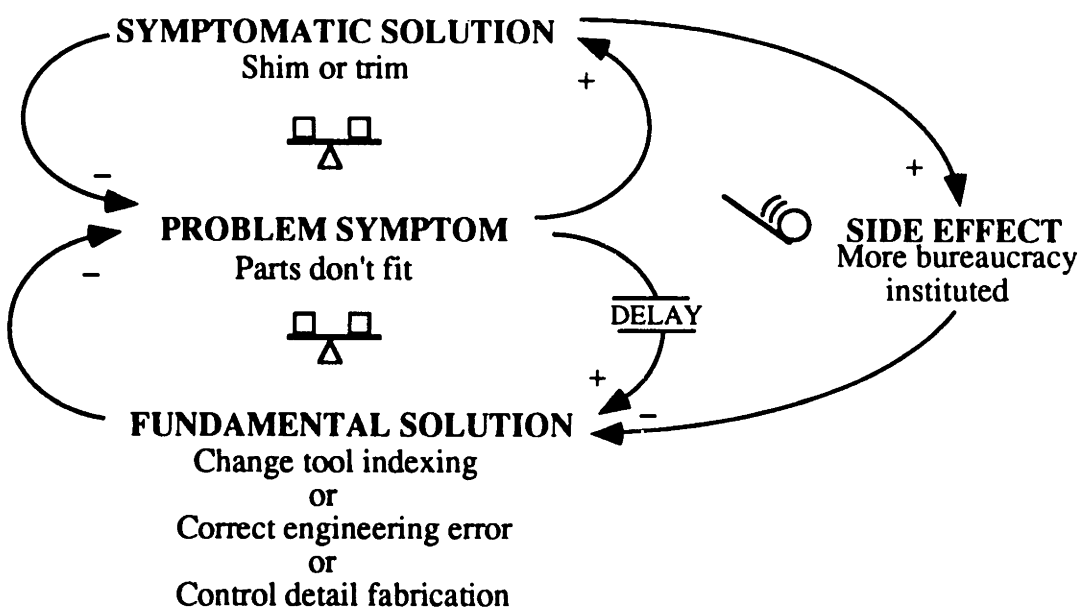

Figure 2.2.2: Shifting the Burden System Structure of Rework

2.3 Boeing's Approach to Managing Variation

Boeing recognizes the high costs of variation and has targeted variation reduction as one of its breakthrough strategies[5]. With the launch of its newest commercial aircraft,

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[4] Peter M. Senge, *The Fifth Discipline* (New York: Doubleday, 1982) 61.
[5] *D6-55596, Key Characteristics: The First Step to Advanced Quality* (Boeing Document) v.

the 777, Boeing developed a new approach for managing variation. The 777 provided an opportunity to start with a clean slate and also to capitalize on computer aided design technologies that had reached maturity since the development of Boeing's last two entirely new aircraft products, the 757 and 767. Recognizing that variation is inherent in every process, Boeing's goal for the 777 was not to eliminate variation but to manage variation throughout the production process, paying special attention to those areas where variation had historically caused the most problems.

Boeing's approach for managing variation on the 777 consists of five integrated elements:

- product definition or design
- identification of key characteristics
- manufacturing plan
- tool indexing plan
- implementation of statistical process control (SPC)

The use of 100% digital definition, the identification of key characteristics, and the use of SPC are new to the 777. The most important aspects of the process are the digital definition and the integrative approach used to define and implement all five of these elements. The plan will not be successful if missing any one of these five elements.

Design build teams containing members from engineering, manufacturing, and tooling are the enabling element that allow integration between the design, the manufacturing plan and the tool indexing plan during the design process. The five elements are discussed below.

Design

The integration between the design and the manufacturing plan is captured using a design-as-built philosophy, where the drawing tree is created to match the actual manufacturing process. The datums on the drawing are physical locations on the parts, rather than points in space, and they correspond to the indexing used for locating parts

during the build process. Furthermore, consistent indexing is used throughout the design tree and the manufacturing build process. This approach greatly enhances the opportunity to control the variation added during the assembly process because part mating features are controlled on the drawing tree just as they are in the manufacturing process.

The use of digital definition and computer solids modeling allows the elimination of engineering errors, especially conditions of nominal interference and gap. Furthermore, with digital data, the tooling can be designed from the same data set as the design without the use of physical models or gages. Using the same data set also ensures that the tool indexing used during the build process accurately reflects what is specified on the drawing.

Key Characteristics

Key characteristics are the features or requirements of the assembly which are the most critical to ensuring the fit, performance and service life of the final product. They are defined during the design process by the design build team. Key characteristics provide the starting point for implementing SPC in the manufacturing process. The use of key characteristics is not intended to loosen or tighten the engineering requirements, nor are they an alternative to proper dimensioning and tolerancing; all dimensions on a drawing are important and should be adhered to. Rather, key characteristics are intended to provide a common focus on those part features which are most important to control to avoid problems during assembly and the service life of the product.

Key characteristics are selected from the top down on the drawing tree. Key characteristics are first identified for top level installations and are then flowed down through the drawing tree in a process which identifies any lower level features which might influence the high level key characteristic. This process is presented in detail by the Boeing document *D6-55596, Key Characteristics: The First Step to Advanced*

Quality. This process results in an explosion of possible features to label as key characteristics.

The intent is to measure all key characteristics as part of an SPC program. While all characteristics of a part are important, the cost of measuring and analyzing every feature outweighs the expected benefits. The emphasis is on limiting the total number of key characteristics for an airplane design to a manageable level. Boeing has established a formal method to identify the "essential few" key characteristics, which is presented in the document referenced above. This method involves rating the features based on three factors, creating a pareto diagram of the results, and then selecting the obvious big hitters.

Manufacturing Plan

The manufacturing plan details the process, sequence of steps, part requirements and assembly requirements for producing the product. In this new process, the manufacturing plan also documents which features are key characteristics along with instructions for measuring these keys in support of an SPC program.

Tool Indexing Plan

The tool indexing plan identifies the method by which the tools will locate parts or assemblies in space relative to one another. With Boeing's new variation management process, the tool indexing will match datums on the drawings. Indexing is established at the top level installation and flowed down through the manufacturing tree. If new indices or datums are required on a sub-assembly because some features of the assembly or installation cannot be used, they are established as a shift from the established index or datum on the installation. This shift in the datum is controlled by a key characteristic. Under the new process, the tool indexing plan will also provide locations for measuring the key characteristics.

Statistical Process Control

The final element in Boeing's process to control variation in the assembly process is the implementation of statistical process control to measure the key characteristics.

Boeing has already established a documented process, called Advanced Quality System (AQS), for implementing SPC at its suppliers. SPC provides feedback within the system to drive continual improvement. Measurements are taken on the key characteristics and analyzed. Improvements are made to bring the process under control, improve its capabilities and ultimately, improve the quality of the final product.

Boeing's plan for managing variation on the 777 is an integrated approach: the benefits of the plan cannot be achieved if any one of the five elements is missing. The plan embodies the continuous improvement philosophy of Plan-Do-Check-Act (PDCA)[6]. The *plan* phase includes developing the initial design and the build plan. The *do* phase includes the actual production of the product with the measurement of key characteristics as SPC data. The *check* phase includes analyzing the SPC data to calculate whether the process is in control and capable. The *act* phase utilizes problem solving tools to establish a process improvement.

2.4 Limitations of Applying Boeing's New Approach on Mature Designs

As noted earlier, Boeing has stated that managing variation is one of its breakthrough strategies. Boeing would like to implement the approach presented in § 2.3 on its mature products: the 737, 747, 757, 767. For these products, the design, the manufacturing plan and the tool indexing plan are already established. This leads to the conclusion that implementing the variation management process simply requires adding the missing elements: key characteristics and statistical process control. However, implementing key characteristics alone is not the panacea for eliminating variation on these mature products.

The misunderstanding about the true requirements of the process to reduce and control variation is pervasive. The number of drawings updated with key characteristics

[6] W. Edwards Deming, *Out of the Crisis* (Cambridge: MIT Center for Advanced Engineering Study, 1982) 88.

has become a new performance measure for many managers. Managers on the older aircraft programs are anxious to identify key characteristics and add them as call outs on the engineering drawings. As a result, variation management has become equated with identifying key characteristics.

The perception is that fit-up problems in assembly are driven solely by detail part variation. If key characteristics are identified on the drawings, then the suppliers will be forced to implement SPC, start measuring these characteristics, and start providing better details. This places the burden of correcting several decades worth of variation problems on the suppliers. It also ignores the fact that problems internal to Boeing are driving many of the variation problems. Even if the suppliers provided perfect detail parts, which never stray from nominal specifications, Boeing would not be able to produce the assemblies without a considerable amount of rework.

One might think of Boeing as the "old" Boeing and the "new" Boeing, where the "old" Boeing builds the mature products and the "new" Boeing builds the 777. Key characteristics cannot solve the variation problems in assembling the mature aircraft because they do not address the problems riddling the old Boeing production system. While the design, manufacturing plan and tool indexing plan already exist, they do not meet the criteria established in the variation management process developed for the 777.

For example, some of the problems with the existing designs and manufacturing build plans are as follows:

- The design is not drawn to match the build process.
- The design, predominantly hand-drawn, contains interference/gap errors.
- The drawing datums do not match the tool indexing.
- The tool indexing is not consistent throughout the build process.
- Tools are fabricated using master models, not actual part definition, giving final authority for part configuration to tooling rather than design.

All of these conditions lead to variation in the build process, and ultimately, costly rework. Key characteristics cannot be expected to correct the variation problems arising from these shortcomings.

The process established on the 777 to manage variation requires an integrated approach to design and production before key characteristics and SPC can be implemented to maintain gains and make further improvements. This process cannot be applied to the mature designs without major revisions to the existing designs, manufacturing plans and tool index plans. Redesigning Boeing's mature aircraft products is neither desirable nor feasible. However, an investment of resources to make major changes to reduce variation and improve product quality holds tremendous payback potential. A focused approach, embodying the spirit of the 777 process, for understanding and reducing variation on the existing designs is presented in Chapter 4. First, however, a case study of the costs of rework in the Door Responsibility Center is presented in Chapter 3 to provide motivation for implementing such a process.

Chapter 3: Case Study in the Door Responsibility Center

3.1 Background of the DRC

The Door Responsibility Center, or DRC, was created in January 1993 as a self-contained, self-managed organization with the sole responsibility of defining, building, delivering and supporting its products. The DRC represents a new approach to organizational structure for Boeing, where organizations have traditionally been designed around functions. This organization was established to validate world-class concepts of production systems and business processes within the Boeing production environment. The DRC's initial objectives were to reduce the following[7] : inventory, cycle time, variation, non-value-added activities, and customer maintenance.

The DRC builds pressurized doors for 737 and 757 airplane production. These doors, along with the quantity of each built by the DRC in 1993, are listed in Table 3.1.1.

737 Doors	# Built in 1993
Forward Entry Door	138
Forward Access Door	12
Forward Airstair Door	51
Overwing Escape Hatch	256
757 Doors	
#1 Right Hand Passenger Door	50
#1 Left Hand Passenger Door	50
#2 Right Hand Passenger Door	56
#2 Left Hand Passenger Door	57
#4 Right Hand Passenger Door	59
#4 Left Hand Passenger Door	59
#3 Right Hand Emergency Exit Door	24
#3 Left Hand Emergency Exit Door	24
Electrical Access Door	64
Overwing Escape Hatch	128
Main Deck Cargo Door (Freighter Only)	5
#3 Cargo Door (Customer Option)	0
Total Number of Doors Built	**1033**

Table 3.1.1: Doors Built by the DRC in 1993

[7] *Leading the Way: Door Product Center Implementation Plan and Executive Summary* (Boeing Document, January 1993) 4.

The DRC includes members from all of the functions who previously supported the design, build and delivery of doors with the important distinction that these employees now report to the DRC rather than their functional groups. The DRC was comprised of 214 people as of November 1, 1993. A breakdown of the labor represented in the DRC is given in Table 3.1.2. A more detailed breakdown is provided in Appendix A.

Direct Labor	64
Inspectors	27
Hourly Shop Support	6
Management	16
Planners and Schedulers	25
Engineering	41
Administrative Support	7
Other	28
Total	**214**

Table 3.1.2: DRC Employees as of 11/93

3.2 The Cost of Building a Door

The organization of the Door Responsibility Center makes estimating the cost of its products straightforward. Given that the DRC has 214 employees and built 1,033 doors in 1993, the aggregate cost of building a single door in 1993 was

$$\frac{\textbf{214 employees x \$189,000/employee/year}}{\textbf{1,033 doors/year}} = \textbf{\$ 39,154 per door}$$

This is based on a fully burdened cost of $ 189,000 per employee, which includes materials costs, overhead and executive compensation.[8] Of course, some doors are smaller and simpler while others are larger and more complicated, and these doors would cost less or more, respectively, than the average. Nonetheless, $ 39,154 represents the order of magnitude of the cost of building a door, and the amount is staggering. Most cars cost less than a single airplane door!

[8]See Appendix B for the source of this calculation.

The organization of the DRC also highlights the high cost of the overhead support structure and bureaucracy that has evolved as a result of rework, i.e. the hidden costs illustrated in Figure 2.2.1. What is more surprising than the cost of the door is that the direct labor contribution accounts for only 30%, as shown in Figure 3.2.1. The overhead to direct labor ratio of 2.3 is indicative of the influence variation has had on the Boeing production system. Overhead and indirect labor in the DRC contribute 70% of the labor costs to build a door. Using an estimated value of $ 55[9] per hour as the labor rate of an average employee, including benefits, this translates to $ 16,676 per door:

$$\frac{\text{150 employees x \$55 /hour / empl. x 2088 hours/year}}{\text{1,033 doors/year}} = \$\ 16{,}676 \text{ per door}$$

In other words, overhead labor and indirect labor together account for 43% of the average cost of a door. Only 57% of the costs are accounted for by direct labor, materials, and capital overhead. On an annual basis of building 1,033 doors, the overhead and indirect labor represent **$ 17.23 million** in costs for the DRC.

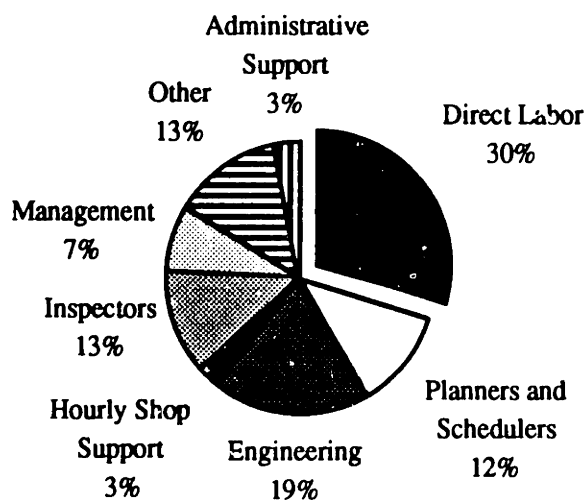

Figure 3.2.1: DRC Direct Labor Versus Overhead

[9] $55 per hour labor rate taken from Boeing Report: *Investigative Report and Recommendation to Engineering on Steering Committee Problem #6* (757 Producibility CQI Team, December 11, 1991) 12.

3.3 757 #4 Passenger Door

The 757 #4 Passenger Door served as the case study for evaluating variation management in the assembly environment. The location of the #4 Door on the airplane is illustrated in Figure 3.3.1. The #4 Door represents a typical passenger door for both the 737 and 757 airplanes, in terms of the structure, the assembly process, and the problems encountered during assembly.

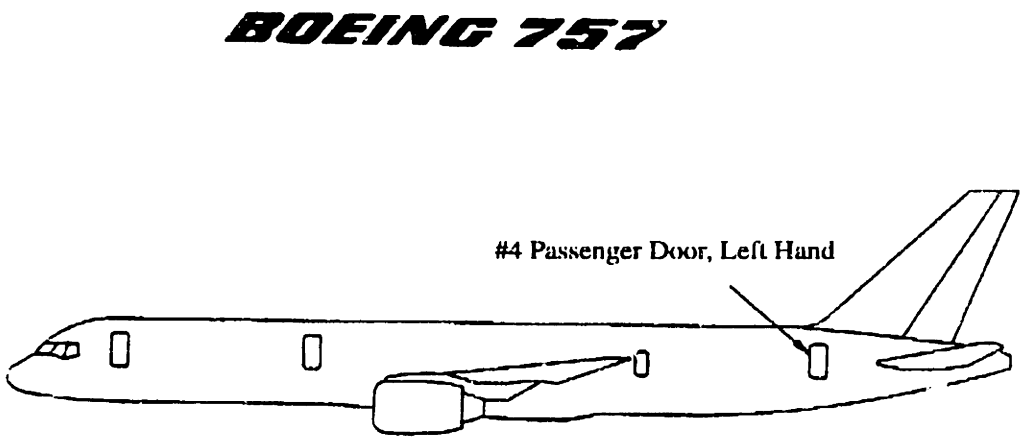

Figure 3.3.1: Location of the 757 #4 Passenger Door

The #4 Door consists of a crate-like support structure, mechanisms for opening, closing and latching the door, and an inner and outer skin. The basic door structure, shown in Figure 3.3.2, consists of over 150 sheet metal components, combined into sub-assemblies and then into the final assembly in a three-tier approach. First, detail parts are assembled into side frames, beams and intercostals. Next the beam assemblies are nested inside of the side frames, and finally the intercostal are nested into the beams during the assembly process. The #4 Door consists of two side frames, six beam assemblies and 22 intercostal assemblies. After the structure is assembled, the outer skin is attached and the door mechanisms are installed. Finally, an inner skin is installed.

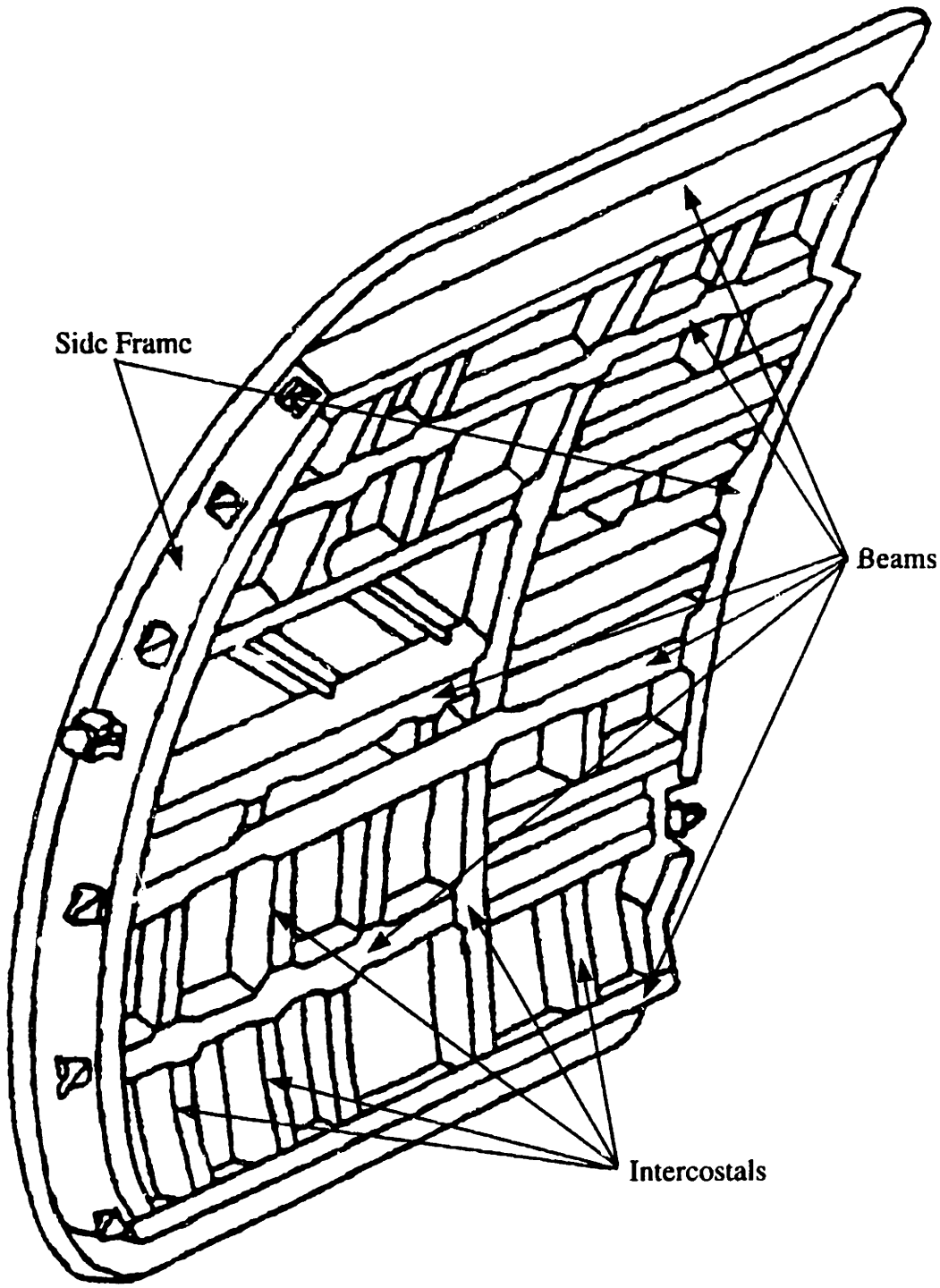

Figure 3.3.2: 757 #4 Passenger Door Support Structure

The door was originally designed with the intent of having all of the structural components built upon assembly without shims. Most of the detail parts are defined right on the installation drawing without any definition of sub-assemblies. This is often referred to as MOA, for make on assembly. While the design allowed a +/- .03 inch tolerance on all dimensions, any variation in detail part tolerances would be accommodated by adjusting the position of the detail parts to fit upon assembly. This philosophy allowed for an engineering design that excluded the use of shims as well as the need for trimming details, provided that the detail parts met the design specifications within the +/- .03 inch tolerance. This approach was intended to provide an assembly design that was robust to part variation.

However, evolution in the assembly process away from the originally intended process created new problems which did not accommodate part variation and resulted in the need for shimming and trimming of detail parts. With demands for increasing production rates during the 1980's, the assembly of most of the door components, such as beams and intercostals, was moved upstream from the final assembly process. While this supported the higher production rates, it created problems. The sub-assemblies could no longer be adjusted upon installation to account for part variations. Given the design tolerances of +/- .03 inches on the details, the first-tier sub-assemblies faced a potential .06 inch gap or interference even if the details were per drawing. This gap or interference would then propagate into the next tier of sub-assembly, creating increasing gaps and interferences. This provides a compelling argument for controlling part variation.

Most of the structural sub-assemblies contain joggles at fit up locations with other sub-assemblies to provide a smooth mating surface for the outer skin. One of the greatest sources of part variation has been the joggles. Typically, the joggles on most details and sub-assemblies have not been controlled within drawing specifications. The suppliers of these parts have had difficulty in establishing capable and controlled processes to produce joggles. The resulting fit-up problems with the skin have created the need for extensive

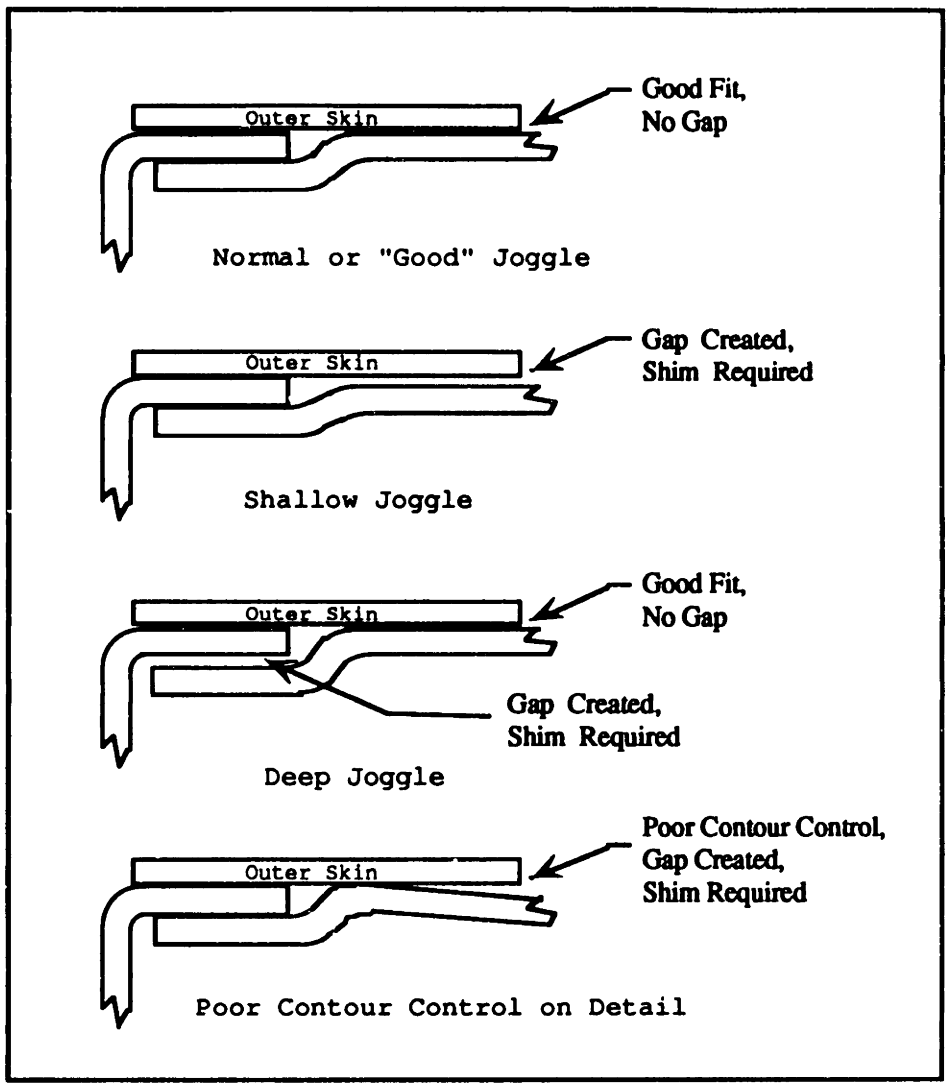

Figure 3.3.3: Shimming Conditions Caused by Joggle Variation

shimming to maintain proper skin contour on the door. Figure 3.3.3 illustrates the various conditions and shimming requirements resulting from poor joggles. Even joggles controlled to drawing tolerances could require similar shimming as a result of detail part variation and unfavorable tolerance stack up.

In addition, the sub-assemblies were being built on "non-designed" tooling. This tooling did not properly locate the details to maintain dimensions on the sub-assembly required for fit-up at the next assembly level. For example, see the intercostal tooling shown in Figure 3.3.4. The critical dimension to hold during assembly of the intercostal is the intercostal height at each end. The tooling pins which position the details during the

assembly process are not located to control this critical dimension. The joggle depth in the intercostal chord and web cannot be tightly controlled during the fabrication process.

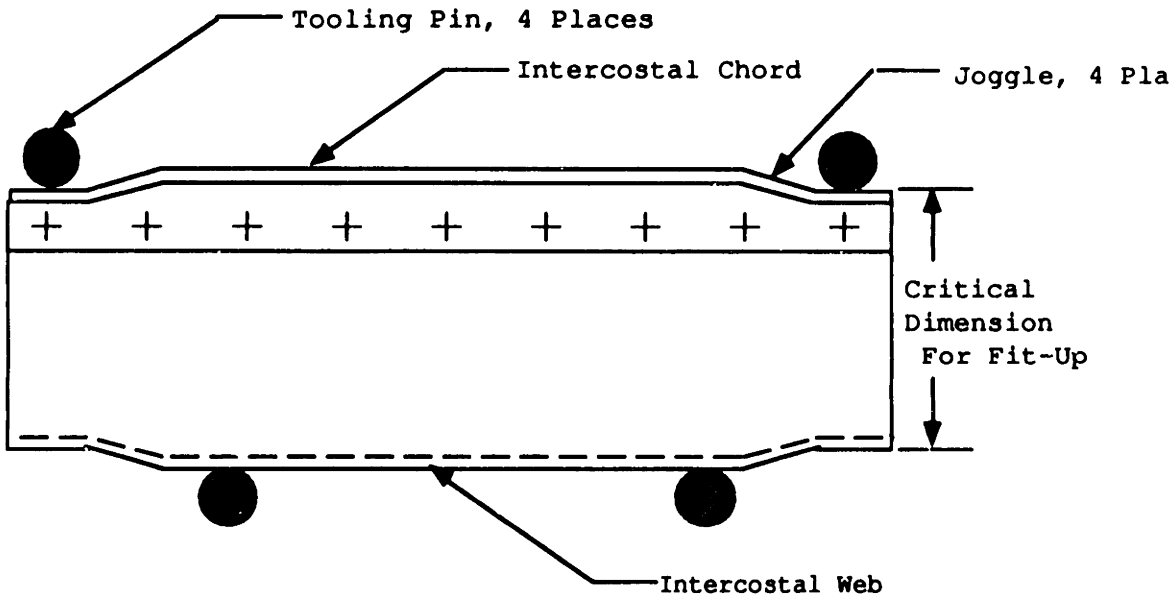

Figure 3.3.4: Non-Designed Tooling for Assembling an Intercostal

The tooling pins which position the intercostal web during build-up are not locating the intercostal web at the ends outside of the joggle zone (see Figure 3.3.4). As a result, when the joggle depth varies, so does the finished height of the intercostal sub-assembly. For this example, a gap or interference between the intercostal and the beam frequently occurred and required rework. For gaps, rework consisted of shimming the gap between the intercostal and the mating surface of the beam assembly to which the intercostal was joined. For interference, rework consisted of removing and scrapping the intercostal chord and attaching a new one at the proper location to insure a proper fit-up.

3.4 Shimming/Trimming Example: Implications on Production Costs

While the original design concept for the 757 #4 Passenger Door was intended to preclude the use of shims and the need for trimming on assembly, the door as built today is riddled with shims and requires several trimming operations for the reasons discussed

in §3.3. Shimming and trimming on the #4 Door were further investigated to determine their contributions to production costs.

The mechanics building the #4 Door provided duplicate shims for every shim they installed during the assembly of six doors. These did not included drawing specified fillers or the large shims normally installed under the endgates. The shims were weighed to determine the average weight added to a #4 Door. The shim locations were analyzed to determine if relaxed pull-up requirements for gaps would allow elimination of shimming. Finally, the production costs for shimming, based on the direct labor hours, were calculated.

The average weight of shim added to a #4 Door was 0.70 pounds. According to the mechanics, the shims collected from the six doors being studied were typical of the shims installed on most #4 Doors. Again, this did not include any drawing specified fillers or the shims installed under the endgates. The endgate shims themselves would have accounted for a large portion of the shim weight added to a door if included in the measurement. Table 3.4.1 provides a breakdown of shim weight by assembly position on the doors. Each reported weight reflects the average of data collected from six doors.

	Ave. Shim Weight (pounds)
Position 1	0.27
Position 2	0.34
Positions 3 and 4	0.08
Average by Door	**0.70**

Table 3.4.1: Average Weight of Shims Installed on the 757 #4 Passenger Door

In Position 1, the door structure is assembled. The shims installed in this position were primarily between the door stop fittings and the frames, though several intercostal-to-beam and very few beam-to-frame join locations were also regularly shimmed. Leaving out the shims in these locations was ruled out as a possibility because the

contour of the door is set by the frame build-up in this position. Pulling up excessive gaps in the structural components would create warpage in the frame, which in turn would require considerable preload when attaching the skin in an attempt to maintain contour specifications.

In Position 2, the outer skin is attached. The shims installed in this position were almost exclusively between the outer skin and the mating support structure. Pulling up the gap in these locations was not an option because it would create wrinkles or depressions in the skin.

In Positions 3 and 4, the mechanisms are installed and the inner skin attached. The majority of the shims installed in these positions are between the structure and the door operating mechanisms. Again, pulling up the gap was not considered viable because critical operating mechanisms were effected by the interface.

The average time spent installing shims and trimming interfering details was estimated by the mechanics to be 41.5 hours per ship set of 757 #4 Passenger Doors, or 21.25 hour per door. Using 40 ship sets of actual labor charge data, the average number of labor hours to build a ship set of #4 Doors was calculated to be 237.2 hours, excluding clean, seal and paint operations. Based on this data, the average amount of direct labor hour spent on shimming and trimming was 17.5%. For the #4 Doors, with seven full-time mechanic/assemblers, this translates into

17.5% x 7 employees x $ 115,000 /employee/year[10] = $ 140,875

annual production costs spent on the institutionalized rework of shimming and trimming the #4 Door. Last year, this would have been equal to $1,200 per #4 Door given that 118 # 4 Doors were built.. Note, this accounts only for direct labor costs and does not consider costs such as inspection, scrap, paperwork, engineering dispositions for rework, etc.

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[10] Assuming a direct labor rate of $55 per hour, including benefits, the annual cost of one worker is $115,000. Note that Boeing counts 2088 hours in a work-year.

The implications of the possible costs of shimming and trimming for the entire Door Responsibility Center are staggering. Assuming that the average proportion of production hours spent shimming and trimming the 757 #4 Passenger Doors is representative of all of ` doors[11], the shop-wide direct labor cost for this rework in the DRC alone would run:

17.5% x 59 empl. x $115,000/empl./year = $ 1.19 million/year

This translates to a direct labor cost of shimming and trimming of $1,150 per door, which does not include any of the inspection, paperwork, planning, scheduling, or engineering disposition costs.

This $1.19 million can be thought of as only a fraction of the price tag Boeing has paid for fire-fighting in lieu of addressing the root cause of the variation problems on the assembly floor. The remaining portion of the price tag comes from the overhead costs of the system that supports institutionalized rework. If the number of overhead employees were reduced by 50 %, which still leaves a heavy overhead-to-direct labor ratio of 1.2, the potential annual savings would be

50% x 150 overhead empl. x $115,000/empl./year = $ 8.625 million/year

The potential to eliminate the $ 1.19 million annual shimming cost alone, much less the potential savings of $ 8.625 million in overhead labor costs, should provide incentive for Boeing and the Door Responsibility Center to make the necessary investments to reduce and control variation on the assembly floor. That money would go a long way toward making the necessary improvements to reduce rework and eliminating the need for most shimming and trimming.

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[11] Shimming on the 757 #2 Passenger Door, which is a comparable structure to the #4 Door, is reportedly much worse according to the mechanics. Some doors may require more or less shimming time, but the 17.5% provides a ballpark estimate.

3.5 Implications on Customer's Operating Costs

In addition to the cost to Boeing, rework affects the quality of the finished product and the costs to the customer. Rework adds weight to the plane, increasing the customer's operating costs in terms of fuel consumption. Furthermore, the customer is left with the lost opportunity costs of being able to carry less passengers or cargo. The shimming example on the #4 Door provides some insight into the magnitude of these costs for the customer.

Shimming typically adds 0.7 pounds to the 757 #4 Door. The #4 Door structure, including the mechanisms but excluding the emergency escape slide, weighs 181 pounds. This translates into an average weight gain of 0.386%. While this seems trivial at first glance, further consideration proves this to be a significant increase. The 757 basic structure, excluding the engines, weighs 90,000 pounds. Assuming shimming of the structure is roughly consistent for the entire airplane, at 0.386%, this translates into a weight penalty of 348 pounds. While 348 pounds seems inconsequential in comparison to the 757 total delivered weight of a 125,000 pounds, it still has a sizable impact on the customer.

The cost to the airline, in present value terms, is $250 per added pound on a 757. This represents only the additional fuel operating costs over the life of the plane and does not consider any opportunity costs or added maintenance costs, etc. At this rate, 348 pounds of shims adds $80,000 to the customer's operating cost for one 757 airplane. While this seems insignificant in comparison to the millions of dollars of added rework costs to Boeing, it is still significant to the customer's bottom line.

Chapter 4: A Process for Reducing and Managing Variation

Tackling variation in the assembly process of the mature designs requires an up-front review of the existing environment on the production floor. Before key characteristics and SPC can be implemented, a clear understanding of how the existing design, manufacturing plan and tooling contribute to variation is required. This amounts to identifying the fundamental causes of variation, and ultimately, of rework. With the causes identified, solutions can be implemented which break the vicious cycle of quick fixes and institutionalized rework discussed in § 2.2.

A proposed process for identifying the fundamental problems and implementing fundamental solutions is outlined in this chapter. This process provides a targeted approach, focusing limited resources on the highest leverage improvements, while also providing a method of approaching the problem within a manageable scope. This process was developed by the author for use by the DRC Variation Management Team, but the methodology had not been used or implemented by the end of the author's internship.

4.1 Overview of the Process

The proposed process was developed by the author after exploring the implementation of key characteristics on products built in Boeing's Door Responsibility Center. The process uses a targeted approach to identify the greatest source of rework in a given shop and focus limited resources on developing a fundamental solution to eliminate the variation and the need for rework. The process embodies the spirit of the approach used on the 777 while taking into account the limitations encountered on a mature design. The process is outlined in Figure 4.1.1.

A more detailed explanation of each step is provided in the following sections. The process is intended to be used by an integrated team with factory personnel, preferably the assembly mechanics, leading the effort. The mechanics building the

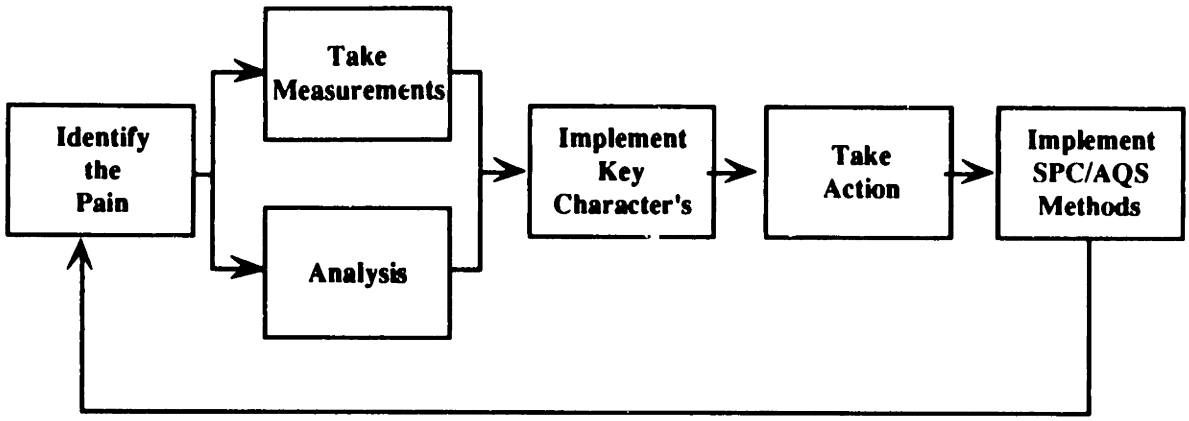

Figure 4.1.1: Proposed Process for Reducing Variation on Mature Designs

product have the best in-depth understanding of the actual production process. They can provide a better understanding of and focus on the assembly process and the problems influencing production. The mechanics will gain a better appreciation of variation and its affect on production costs and product quality. Giving them control over the process and the power to identify the necessary changes will provide a better chance of success than changes proposed by support groups that do not live on the production floor.

4.2 Where to Start

The initial step is to identify the pain in a given assembly shop. The key is to identify which product or operation or area of the shop is suffering the most from rework. Data of the following types are collected and rank ordered into pareto diagrams to highlight the most glaring areas of trouble: (This list is not exhaustive.)

- Complaints from downstream production
- Complaints from airline customers of delays, categorized by door or by failures of certain mechanisms (Scheduled Interruption Reports)
- Number of rejection tags per part or production cell
- Cost or length of time required to complete rejection tag disposition
- Amount of scrap generated by rework for a part or production cell

- Number of Greenlines[12] by part number
- Labor hour over-runs by production cell
- Average hours of overtime by production cell
- Trends in flow time by product or production cell

The data collection is intended to pinpoint what areas of chronic rework generate the highest costs for the shop. The use of pareto diagrams focuses restricted resources on an effort to alleviate the greatest pain first.

Having identified the greatest source of pain for the shop, the team completes the remaining steps of the process focused specifically on that problem. While evaluating the problem and identifying the root causes, the team will recognize other problems effected by the same causes. The team should stay focused on the problem at hand but recognize how changes may influence other aspects of the assembly process. This approach narrows the scope of the task to a reasonable size. It allows the team to tackle a manageable task rather than being overwhelmed by the problems associated with an assembly in their shop.

4.3 Taking Measurements

Once the problem to address has been identified, it should be verified. Taking measurements provides data to verify the problem, as well as when and where it is occurring. They also verify whether variation is involved with the problem. Measurements should be taken throughout the analysis and documentation stage. This allows analysis of whether the problem or process is changing during this time frame.

Measurements should be quick and simple, though repeatable. Keep a simple record of measurement locations and techniques. A "wit and muscle" approach will provide the data needed without high costs. The measurement techniques will be

[12]A Greenline is the extension of a rejection tag disposition to a block of planes, usually 20 airplanes, which results when a rejectable condition consistently occurs on several consecutive airplanes. The Greenline provides engineering coverage to rework a block of airplanes until the root cause of the problem is identified and alleviated, whether through a drawing change, tooling change, etc.

evolving as the team learns more about the problem, and the need to measure a particular feature or part may change. For this reason, measurement plans and techniques will not be locked in until later in the process when SPC is being implemented. Flexibility is a key requirement because the production environment is dynamic. With this in mind, the team should avoid creating a bureaucracy around the measurement taking process, and they should also avoid the desire to create a "showcase" measurement system.

4.4 Analysis

Analysis is required to identify the root causes of the problem. This process includes verifying the production process and documenting any discrepancies in the engineering design, the detail part dimensions, the manufacturing plan and the tool indexing plan. The analysis focuses first on locating where the problem is being introduced into the production process and second on determining the root cause of the problem. To locate where the problem is being introduced, the following steps are taken:

- Identify the symptom, i.e. a chronic gap between mating parts.
- Take measurements of the affected parts and decide if variation is involved or if parts are being consistently mislocated.
- Take measurements one step upstream in the production process and determine if the parts are changing between the two production stages, i.e. is the problem or variation being introduced at this stage of production.
- If the parts are unchanged in both stages of production, step back to the next stage upstream and take more measurements.
- Continue this process until the production step is identified in which the problem is being introduced.

Having identified where the problem is being introduced into the production process, the focus turns to an analysis of the root cause of the problem. Note that some problems may be very complex and evolve through several production steps. Identifying the first

process step where the problem is introduced is crucial to correcting the problem. If downstream steps are corrected first and upstream steps are corrected later, the effect of the change to the upstream step may cascade down through the production steps and create new problems.

With this in mind, the analysis of the root cause of the problem involves investigating the four main sources of variation highlighted in Figure 2.1.1: the manufacturing process, the tool-indexing plan, the detail parts, and the engineering design. These four areas may be investigated simultaneously, though analysis of the manufacturing process should be first priority when they are not. The analysis of each of these four areas is discussed below. The analysis should encompass all of the production steps from where the problem is introduced to where the problem ultimately manifests itself. This will require the team to work closely with their internal, and possibly, external customers.

Manufacturing Process

Verify that the manufacturing process actually used is consistently followed and is in agreement with the manufacturing plan. Create a process flow diagram of the actual process used, including all of the process steps and compare this to the planning. Investigate whether the planning instructions are clear and adequate. Document any discrepancies. The most important question is whether or not the process is consistent. Agree on a consistent process to be followed whether or not it agrees with the manufacturing plan. The issue of whether to change the plan or the process will be addressed in § 4.6.

Tool Indexing Plan

Verify that the methods and tools actually used to locate parts are consistently followed and are in agreement with the tool indexing plan. Document any discrepancies. Again, the most important question is whether or not the process is consistent. Agree on a consistent process to be followed whether or not it agrees with the tool indexing plan.

Analyze whether the tool indexing plan provides a consistent use of indexing throughout the production steps being analyzed. Investigate the possibility of tool wear. Also investigate whether the tool indexing plan is coordinated with the datums on the engineering drawing. Document any discrepancies.

Detail Part Variations

Verify whether the detail parts are being made to drawing specifications. Details are frequently available in inventory and may be measured before they are needed for production. When analyzing the details, the questions to be answered are whether they deviate from the engineering dimensions or exhibit variation within the specified engineering tolerances. If the detail parts do not meet engineering requirements or exhibit variation beyond the specified tolerances, communicate this information to the supplier. Problems with deviation from specification can be corrected by adjusting the fabrication process without respect to process capability and control. Problems with variation require actions to bring the fabrication process under control and up to capability requirements.

Engineering Design

Analyze the engineering drawing for items that may contribute to the problem. Does the drawing provides adequate definition of the details; are additional views required? Verify that the details are dimensioned properly, and perform a tolerance analysis to determine if tolerance stack-up is contributing to the problem. Check for engineering errors including nominal interferences or gaps. Also verify that the datums are appropriate and adequate, and verify that they are coordinated with the tool-indexing. Document any discrepant conditions or suggested improvements.

The root cause of the problem should be exposed or uncovered by the analysis of the four areas discussed above. Measurements collected throughout this analysis provide the data needed to verify the problem and its causes. Several causes may exist, and the

solution may entail making several changes simultaneously. Section 4.6 discusses how to proceed from analysis to action, based on the data collected, the results of the analysis, and any resource limitations constraining the choices.

4.5 Identify and Document Key Characteristics

The analysis and collection of measurement data up to this point provide a solid starting point for identifying and documenting the key characteristics for the product. As part of their quality system for suppliers, Boeing has provided a documented process for identifying characteristics and selecting the key characteristics: *D6-55596 Key Characteristics, The First Step to Advanced Quality*. The process emphasizes selecting the essential "few" key characteristics, recognizing the trade-off between the cost of measuring and tracking the keys and the expected benefits they provide. Once identified, document the key characteristics.

Part of identifying the key characteristics is determining how they will be measured. The experience gained taking measurements during the analysis will greatly aid this decision. The key characteristics will be measured as part of an SPC program, to provide immediate feedback to the operators about the state of the assembly or production process and to allow continuous improvement of the process. With this in mind, identifying measurement locations on the existing tooling, or adding measurement features to the tooling, will facilitate having the operator or mechanic take his own measurements. Document the changes required for tooling and the manufacturing plan to include these measurements.

4.6 Take Action

Having identified the root cause of the problem, management can prioritize resources to implement solutions. Revisions to each of the following may be required: the engineering drawings, the tooling, the tool-indexing plan and the manufacturing plan.

Implement as many of the changes identified by the analysis step as the resources allow.

At a minimum, creating a consistent process is mandatory, even if the process consistently produces bad parts. This will provide a stable starting point for implementing improvements. Otherwise, the effect of improvements to the tooling or to the drawings, etc., will be lost in the variation caused by an inconsistent process.

The key characteristics may be added to the drawings as the drawings are revised. However, they should be added to the manufacturing plan immediately, allowing the mechanics to start taking measurements. If the plan for steady-state measurements of the key characteristics will take time to implement, develop an interim measurement plan that the operators can implement immediately. Perhaps the best steady-state plan will evolve as the operators gain experience taking measurements and monitoring variation.

4.7 Maintain the Gains with SPC

Implementation of statistical process control is the logical next step. Boeing provides a documented process for implementing statistical process control in *D1-9000, Advanced Quality System for Boeing Suppliers,* known as AQS, which applies equally well to internal Boeing operations. SPC provides the means of tracking and maintaining the gains made from the initial steps taken to improve the process and remove variation. It also takes this further and allows continual improvement in the process, leading to increased process capability and control, increased product quality, and ultimately, decreased production costs.

4.8 Closing the Loop

The goal of this process is to provide a continuous improvement loop. The problems having the greatest impact on assembly are tackled first, which focuses limited resources on achieving the greatest benefit. Several problems can be investigated simultaneously, or when resources do not allow this, the problems can be approached one at a time using the pareto charts created in the first step to establish the order. Each pass

through the process will take less time as the team experiences the learning curve effect. Also, as solutions to new problems are identified and implemented, the SPC analysis of the previously identified key characteristics will help identify how new changes affect the assembly process.

This process focuses on production as the leverage point for making change, recognizing that engineering, tooling and planning are support functions to producing a product rather than products in themselves. Changes needed in the production process will drive the changes needed in design, tooling and planning. Also, the process provides a method for identifying a manageable effort and targeting limited resources at effective and measurable improvements.

More importantly, this process emphasizes finding the fundamental sources of problems and implementing fundamental solutions rather than the quick fix. This will break the "Shifting the Burden" cycle described in § 2.2, allowing Boeing to greatly reduce the need for rework in the production process. As the need for rework declines, the massive overhead systems supporting rework operations can be dismantled, generating significant cost savings.

Chapter 5: Conclusion

Variation is a major source of waste, rework, non-value added costs and lowered product quality. As shown by the case study in the Door Responsibility Center, where only 16 distinct aircraft doors are built, the potential annual direct labor savings for eliminating most shimming and trimming operations is $1.19 million. Furthermore, shimming and trimming account for only a small portion of the rework activities that occur in assembly. Note that this figure does not include any of the savings associated with reducing materials, scrap, paperwork, support or overhead activities. The potential savings, when expanded across the entire airplane to include all of the hidden costs, in addition to direct labor savings, would be astronomical.

Recognizing the cost and quality impact of variation on production, Boeing developed a program for reducing and controlling variation on the 777. This program is well suited to new designs; yet, it cannot be easily transferred to Boeing's mature products. Critical to the success of this program are a well-coordinated design, manufacturing plan, and tool-indexing plan, in combination with the use of key characteristics and statistical process control.

Boeing wants to implement this variation management program on its existing, or mature, aircraft as well. The common belief is that the mature products are only missing the identification of key characteristics and the implementation of SPC to measure these characteristics. However, implementing key characteristics and SPC, alone, on the mature aircraft designs will not even begin to address the variation problems occurring in production. The variation problems plaguing the assembly process are not solely caused by variation of detail part or assembly dimensions within the specification. Key characteristics focus attention specifically on design features; they do not address inconsistencies within and between the design, the manufacturing plan and the tool-indexing plan.

In order to truly address the assembly problems arising from variation on these mature designs, a comprehensive analysis of the design, the manufacturing plan and the tool-indexing plan, as intended and as used in practice, is required. A process for doing just that was proposed in Chapter 4.

5.1 Benefits

Reducing variation in the production process holds the potential of tremendous cost savings to Boeing. To put the savings in perspective, reducing shimming alone could save the customer $80,000 in fuel costs for each 757 and save Boeing millions of dollars in direct labor costs. The direct labor savings in the Door Responsibility Center alone for eliminating most shimming and trimming would be $ 1.19 million annually. This represents a tiny fraction of the production costs which could be saved by reducing shimming on the entire airplane.

The emphasis, however, is provided by recognizing that almost 40 % of direct labor is spent on one form or another of rework and that the overhead costs of supporting an airplane through the production process grossly exceed the direct labor. The overhead structure has mushroomed over time to support the rework requirements of the system, adding all of the hidden costs shown in Figure 2.2.1. Reducing and controlling variation provides the potential of eliminating a significant proportion of the rework encountered today. Along with that is the potential to dismantle the costly overhead structure currently required to support rework, bringing the overhead to levels more typical of world-class manufacturing companies and cutting costs by more than 50 %. Imagine the carrot of reducing direct labor by 40% and the overhead labor and associated costs by 50 % or more, and then consider what incentive this should provide for reducing variation.

5.2 Implementation

Boeing is currently implementing a training program to address reducing variation in the production process of its mature airplanes. The program makes use of master trainers throughout the company who provide a consistent approach and methodology for tackling variation. These master trainers are responsible for training the various production organizations how to implement the variation control process. At this time, some of the ideas and process presented here for identifying and reducing the sources of variation are being taught and implemented in this program.

Also, responsibility centers will play an important role in this arena. The responsibility center organizational structure, by its very nature of self-containment, will highlight the costs of doing business. By dedicating the support staff needed to support a set of production operations to the responsibility center, the incredibly high levels of overhead will be exposed. Responsibility centers are well-positioned to reduce variation and the resulting rework and to transfer production responsibilities to the mechanics in team environment.

5.3 Further Research

While the mature airplane programs at Boeing do not have the benefit of starting over with a clean sheet of paper, like the 777 program, they can consider the option of adopting some of the new technologies available today. One example is digital definition. While it would not be practical in any sense to start designing the existing airplanes from scratch, many of the existing drawings could be digitized. However, digitizing drawings is not the same as and does not reap the benefits of digital definition. A considerable amount of work and analysis would be required, in addition to the digitizing effort, to create 3-dimensional solids models and eliminate the designed-in interference and gap conditions of the existing drawings.

Further research might entail quantifying the costs of an effort to digitize and refine the design of one of the existing airplanes and then comparing these to the potential production cost savings that would result from greatly reducing variation in the production process. The costs of implementation are not easy to estimate and would have to include any capital expenses to update the production tools and facilities.

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Appendix A

The 214 employees in the Door Responsibility Center are broken down into functional responsibilities as follows:

SHOP

Direct Labor	Assemblers/Installers	50
	Mechanics	9
	Painters/Sealers	5
Inspectors	Inspectors	27
Shop Support	Shop Support (Storekeepers, Dispatchers, Coordinators, Expediters, etc.)	6
	Total	**97**

SUPPORT AND OVERHEAD

Management	Management	16
Planners and Schedulers	Planning	15
	Industrial Engineering	10
Engineering	Engineers	16
	Liaison Engineers	3
	MR&D Engineers	1
	Tool Engineers	10
	Tool Fabricators	5
	Drafters	6
Admin Support	Administrative Support	7
Other	Business Management (HR, CQI, Finance, Training, PC Support, etc.)	12
	Customer Service	4
	Facilities	1
	Miscellaneous Support (Master Scheduler, Buyers, Statistician, Technical Interface, Customer Coordinator, etc.)	11
	Total	**117**

TOTAL HEAD COUNT	**214**

Appendix B

According to the 1993 Boeing Annual Report, Boeing had $ 25,438 million in revenues with an average of 134,400 employees in 1993. This translates into total costs $189,000 per employee to build the products Boeing sells. Note, this figure includes all overhead, capital expenses, material costs, supplied parts costs, paperwork costs, executive compensation allocation, etc. Using this $ 189,000 per employee figure allows the author to make an order of magnitude estimate of the cost of producing aircraft components, including all operating costs incurred, without revealing Boeing proprietary cost data.

This approach provides only a gross estimate of the costs to build an airplane on a per employee basis. It assumes that costs are spread equally across all operations. For material costs in particular, this is not an accurate representation because some components on the airplane have much higher material costs and much lower labor contents than others. However, the intent is to provide only a rough estimate of the cost of production for any given portion of the airplane. Using these figures provides a rough cut at identifying the total costs of an assembly or component based on the labor hours, direct and indirect, allocated to that component.

While estimating the number of employees from all the various support functions who would support the production of a given assembly is usually quite difficult, the unique organizational structure of the Door Responsibility Center has provided a close estimate of all of the employees needed to build the doors built by the DRC. This number, combined with the average cost per employee to build an airplane, allows a ballpark estimate of the cost to build an airplane door. The estimated costs do not precisely reflect the true costs, but they do provide an order of magnitude estimate of the true costs.