Hardware Variability Corrective Action in Boeing 777 Final Assembly

by

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B.S. Chemical Engineering, New Jersey Institute of Technology, 1985

Submitted to the Sloan School of Management and the
Department of Chemical Engineering
in partial fulfillment of the requirements for the degrees of

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Abstract

This thesis studies the effect of hardware dimensional variation and the methods used to cope with it in the final assembly of Boeing 777 airplanes. It shows that:

- manufacturing process capability, assembly constraints, and integration risk were not adequately considered in the design of engineering tolerances.
- customer-supplier incentives are often misaligned along the manufacturing channel causing variation to be knowingly passed downstream.
- insufficient planning for corrective action occurred in the design stage.
- it takes tremendous effort to analyze and correct problems once they reach final assembly.

The result is a manufacturing process that is statistically incapable of meeting engineering tolerances and hence must rely upon inspection and rework in order to meet the strict quality requirements demanded of the final product. Accepted norms incite that variation be washed into areas where it remains undetected until latent stages of assembly. In final assembly the problems caused by upstream hardware variation are extremely difficult to analyze and correct because of the distance from the source and because existing structures were not designed in anticipation of them.

The need for corrective action is driven largely by Boeing's uncompromising standard of perfection. After inspection and rework the product delivered to a final customer is virtually flawless. The superb quality that characterizes a Boeing 777, however, comes at a manufacturing cost that could be significantly lower. The thesis makes several general recommendations to accomplish the goal of lowered cost through improvements in existing processes and design considerations for future generation airplanes.

The study utilized a "hands-on" case approach to an actual assembly problem to analyze the effects of hardware dimensional variation, organizational dynamics, corrective action processes, and hardware measurement systems. The immediate project goal was to add value to Boeing 777 Division in terms of cost, quality, delivery, and customer satisfaction.

From the specific case, insights were gained concerning general factors that caused the problem and prevailed against a root cause solution. The premise of this approach is that the greatest learning about an organization's deeply held values and unstated assumptions can be obtained when one tries to change something. Areas of strong resistance may indicate places where entrenched beliefs are rooted. Armed with an "insider's" perspective it is possible to identify high leverage opportunities that are not visible to an "outsider".

During the last third of the internship an assembly model called Datum Flow Chain (DFC) analysis was utilized to compare the actual method of technical problem solving used to that which might have been achievable using DFC. The DFC analysis revealed consistent datuming for the problem in question (section 44 body panel aft skin edge station) and uncovered an inconsistency with respect to frame stationing. This demonstrates the value of the DFC as a tool to identify potential assembly problems during product and process design before production operations begin.

Competent follow through by 777 Process Engineering brought to the surface the fallacy of a basic assumption about the accuracy of Boeing tools and tooling surveys. Their work reconciles several disturbing questions that were unanswered when the internship ended. The general lack of sensitivity to measurement uncertainty is a pervasive problem along the entire manufacturing channel.

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Professor Roy Welsch, Sloan School of Management
Dr. Daniel E. Whitney, Department of Mechanical Engineering

Acknowledgments

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I thank my advisors, Professor Roy Welsch and Dr. Daniel Whitney for their assistance throughout the project. Their expertise was a source of challenge that helped me gain much from the experience and pushed me beyond what I could have accomplished alone. Thanks also to Dr. Whitney's two [former] students, Krish Mantripragada and Jeff Adams, for their ground breaking work at 777, their reports, and the tutorial sessions.

Thanks to those who added greatly to this document through review and suggestions: Professor Charles Cooney, Mr. Wencil McClenahan, Professor Roy Welsch, and Dr. Dan Whitney.

I thank the Boeing employees at the internship site who took time from their many responsibilities to participate in the project. John Edgington and Dave Mullenix in Final Body Join lived with the case problem for over one hundred airplanes. They suggested that it would be a worthwhile internship project and important to Boeing if resolved. I further thank Dave Mullenix for the wealth of Boeing cultural insights he shared with me. Charlie Schweigert and Dave Watters in 777 Process Engineering did the real work to preclude problems from reaching Final Body Join. They developed predictive models and moved rework upstream where it could be managed. I am indebted to them for much of this thesis. The 777 Process Engineering Team invited me into their work areas, helped me take measurements, and showed me how to navigate the plant and data systems. Kirt Butler, Steve Doty, Gary Von Erichson, John Levandowski, Richard Matros, Sam Phipps, Pat Roybal, Steve Speece, Joe Westover, and Ted Yasin were invaluable resources. Thanks to Gary Zinter for the diagrams in the Appendixes and again thank Richard, Charlie, Ted, Dave Mullenix, and Dave Watters for the follow up emails and data that continued for months after the internship ended.

I thank 777 Final Assembly Directors Ms. Elizabeth Otis and Mr. Jackson Chao for making me welcome in their airplane factory. Their personal example inspired and motivated me to contribute. I thank Body Structures MBU manager Mr. Tim Copes who, despite incredible demands, made time to host my internship. Most importantly, I thank Mr. Wencil McClenahan, the 777 Process Engineering Manager for making my internship a truly rewarding personal and professional experience. Wencil is mounting a grass roots revolution in the way that Boeing approaches corrective action. The task before him is enormous and he receives no corporate level support as do other strategic manufacturing programs. Wencil is one of the finest individuals I have ever worked for.

To my parents, Gundi and John, thank you for your prayers and support, always.

To my wife, a source of inspiration and strength throughout the LFM program.

Thank you Jesus my Lord, for saving a wretch like me.

Disclaimer Statement

Airplanes in Boeing 777 final assembly are identified by an airplane effectivity[1] number and a line number. Effectivity numbers convey configuration information and are of the form WA001, for example, which corresponds to line number 1, the first 777 built. Line numbers are unique sequential assignments to identify an airplane's relative position within the planned airplane production order. Trend analyses are performed with airplanes sequenced according to line numbers.

Airline customers order specific line numbers before they are built and a detailed *Customer Inspection Process* constitutes an integral part of the airplane production cycle. On site customer representatives, or their designees, are included in meetings and participate in planned inspections of aircraft assemblies, installations, and closures. Customers are apprised of any significant rework necessary to ensure that Boeing's strict quality assurance requirements are met.

This thesis is concerned with corrective action due to component variability that is inherent within any production process. Measurement data and information concerning rework are presented to allow a manufacturing systems analysis of a specific problem. Line numbers are disguised because of the risk of misinterpretation of the information if applied outside of the intended context. Chronological sequencing is retained but two dummy structures (actual line numbers S/T and F/T for static test and fatigue test, respectively) are inserted into the data series to preclude association of plotted data with a line number by counting the number of data points from the beginning. Disguised line numbers remain consistent throughout the document.

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[1] Appendix 6 contains a glossary of Boeing specific terms, acronyms, and definitions.

Table of Contents

1. Chapter 1 - Introduction

The author was assigned to a six month internship with the Process Engineering (PE) Group of Boeing 777 Division's Final Assembly Plant in Everett, WA. At the time of the author's arrival in June of 1997 the factory was completing assembly of the ninetieth[2] 777. By the time the internship ended an additional forty airplanes had been produced and line number (L/N) 130 was being completed.

Process Engineering is a team of 22 engineers who report to the factory manager through Wencil McClenahan, the Process Engineering manager, but they are functionally part of the Body Structures Manufacturing Business Unit (MBU). The charter of PE is to apply structured engineering principles to the resolution of airplane manufacturing problems. There are other groups whose charter it is to resolve manufacturing problems but PE is unique in that they are more removed from the operational mainstream and that they apply analytical tools to characterize the manufacturing process as a *system* that produces airplanes.

In his book The Fifth Discipline, Peter Senge proposes that there are multiple levels of explanation in any complex situation as depicted by the following diagram[3]:

Systemic Structure (generative)

↓

Patterns of Behavior (responsive)

↓

Events (reactive)

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[2] These approximate line numbers are the only actual ones given in the thesis. This is to give the reader a sense for 777 cumulative production and rate.

[3] Page 52.

Event explanations are the most common in contemporary culture and pervasive in manufacturing corrective action organizations. Senge acknowledges that current reality (such as meeting airplane delivery requirements at Boeing) may require reactive behavior (symptomatic solutions) and that in such instances groups that are apart from the everyday mainstream (e.g. 777 Process Engineering) are particularly useful devices to move to higher leverage solutions. Pattern of behavior explanations focus on identification of longer term trends and thus begin to break the stronghold of reactive thinking. In the structural explanation one seeks to identify what causes the patterns of behavior. The structural, or systems level approach is the least common yet most powerful because it recognizes that structure produces behavior which in turn causes events. Thus events are distributed outputs of the underlying system. The emphasis of Process Engineering is to break away from the focus on events in order to affect problem solutions at a fundamental (root cause) level.

The Process Engineering approach is often in diametric conflict with accepted norms. In the latter view, each airplane is unique and problems are solved as though they were isolated events. Plant information, measurement, incentive, and data systems reinforce this view and the organization has tremendous competence in the application of "fire-fighting" methodologies. The approach is pragmatic and often appropriate but an unfortunate consequence is that it is myopic and results in embedded workarounds and institutionalized rework practices. These have become so entrenched that few recognize a systemic pattern of symptomatic problem solving with attendant side effects and atrophy of fundamental solution skills.

The purpose of discussing structural influences on behavior and events at this point is to lay the foundation for a premise that under-girds the thesis. Boeing's system of developing and building airplanes is designed to give the exact results that are being obtained: the best airplanes in the world, delivered on time, at an extremely high manufacturing cost.

The internship was initially undefined with respect to a specific manufacturing issue. The only firm requirement was that it study hardware variability corrective action. After several weeks in the factory the following goals were agreed upon:

- Identify and exploit a hardware variability reduction opportunity with real time cost, quality, and delivery consequences.
- Develop an insider's understanding of critical issues that hinder hardware variability control (HVC) in 777 manufacturing.
- Apply the specific learning gleaned from above to develop general recommendations to improve the existing corrective action process.

1.1 Thesis Chapter Overview

This thesis contains the following:

- In Chapter 1, an introduction.
- In Chapter 2. an overview of 777 final assembly and top level airplane requirements.
- In Chapter 3, a description of the relevant assembly process and the case study problem.
- In Chapter 4, a description of the steps taken to diagnose the problem using in-place systems.
- In Chapter 5. an analysis of the problem using local measurements.
- In Chapter 6, an analysis using datum flow diagrams.
- In Chapter 7. a discussion of results and additional follow up with Boeing since the internship.
- In Chapter 8, conclusions and recommendations.

2. Chapter 2 - 777 Final Assembly and Top Level Airplane Requirements

2.1 Introduction

This Chapter presents the background information for the internship project. It begins with a discussion of the 777 program and describes several considerations that make it unique. This is followed by an overview of the 777 final assembly factory and the top level airplane requirements that describe hardware characteristics demanded of the final product.

2.2 The 777 Airplane Program

The 777 program was developed in response to airline customer interest in a Boeing airplane that would have a passenger capacity between that of the 767-300 and the 747-400. After several years of assessing market preferences and conducting feasibility studies Boeing announced the launch of the 777 into production in October 1990. The design is based on market needs and customer preferences resulting in superior cabin spaciousness and flexibility, enhanced reliability, and lower operating costs than its competitors (The Airbus A330 and A340 and the McDonnell Douglas MD-11).

In addition to obtaining significant customer input, Boeing followed a design process that was different from that of previous generation airplanes. The key attributes of this process included:

- Co-located Design Build Teams (DBT) - Personnel from engineering and manufacturing were physically located near one another to facilitate a more coherent interface between the two groups and a more robust design.
- Concurrent Product Definition (CPD) - Engineering activities were integrated such that releases occurred only once and on time.
- 100% Digital Product Definition (DPD) - Tubing, wiring, blankets, cabling, system attachment points and production illustrations were developed entirely in a digital environment.
- Digital Pre-assembly (DPA) - Aircraft parts were modeled in three dimensions and assembly was simulated in advance of production on computer.

- Integrated Work Statement (IWS) - An evolving statement of the detailed parts, assemblies, installations, plans, and tools that comprised the design was developed.
- Hardware Variability Control (HVC) - A focused method of improving aircraft assembly operations that involved identification of key interfaces was utilized.

Boeings efforts on the 777 seem to be fruitful and the program is replete with success stories and world records. On schedule in 1994 and 1995, the first 777s were flown and delivered with no prototype. A 777 established a Great Circle Distance Without Landing record by flying 12,255 statute miles and later the same aircraft completed a record setting world circumnavigation. The 777-300 is the longest commercial jetliner in the world and the Everett production facility is the largest building in the world. Customers are delighted too. In July of 1997, when the 100th 777 was being built, orders for 323 airplanes had already been received. This gives the 777 a formidable 67 percent of its market while its three competitors share the remaining 33 percent.

2.3 Overview of 777 final assembly

The Boeing 777 final assembly plant in Everett, WA employees 3000 people and rolls out an airplane every three or four days depending upon the planned production rate. A strong sense of respect for time pervades the organization. Schedule compliance is heavily emphasized and the importance of meeting delivery commitments is stressed at all levels. Meetings, appointments, shifts, and major crane and airplane movements begin and end crisply and on time. When this fails to occur, for whatever reason, there is sensitivity to the fact that an important and deeply held value is compromised.

The 777 has over one hundred and fifty thousand unique engineered parts (in addition to over two and one half million fasteners) supplied by internal and external vendors. All work in the factory takes place in dedicated shops known as control codes which are abbreviated CC followed by a number that identifies their function (for example CC335 is responsible for assembly of the wing center section). Everett integrates body, wing, and empennage sub sections and performs ten major fuselage joins (see section 2.3.1 and Appendix 1). The last two joins occur in final body join (FBJ or CC131) where the forward (section 41/43) and aft body (section

46/47/48) sections are joined to the wing center stub (section 44). In FBJ, the factory bottleneck, the airplane takes the appearance of the finished structure.

Boeing's uncompromising standard of perfection, extremely tight dimensional tolerances, regulatory requirements, and the enormous number of critical interfaces give frequent rise to the need for corrective action[4] due to inherent variation. Some problems are single events with an identifiable cause and others are due to variation in major body structures for which the part-to-part fit is not observable until the sections meet at FBJ. The latter depends on the interaction of several variables and often occurs at a great distances from the source. In such cases diagnosis is very difficult because of technical and human factors, the former of which is often easier to address. Low airplane production rates (compared to automobiles or photographic pack film for example), type and quality of data, organizational and cultural complexity, measurement and incentive systems, and a myriad of other factors combine to militate against root cause analysis and resolution. The following sections discuss the 777 final assembly process.

2.3.1 777 Major Body Section Joins

Ten major body joins are performed (see Appendix 1) on completed body sections to produce a finished 777 airplane (Appendix 2 shows the 777 manufacturing assembly sequence). Body sections are built on site in Everett "back shops" from subassembly panels supplied by internal and external vendors (see Appendix 3 for a 777 make buy diagram). Body joins, or simply joins, are best described as the bringing together of two cylindrical sections of fuselage (or a wings to the center stub) and fastening them into either a stove-pipe or butt joint coupling. In final body join (see Appendix 4 for a factory layout) the forward and aft body sections are joined to the wing center section in stove-pipe connections. These are called the forward join and the aft join, respectively.

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[4] Corrective action means exactly that. Any condition that could affect airplane safety, service life, operating costs, or maintainability are resolved before the airplane is delivered. Anything requiring corrective action is reviewed by QA, Engineering, and Manufacturing in a formal process that ensures that the product is not compromised with respect to these requirements.

Massachusetts Institute of Technology students Mantripragada and Adams studied the forward join in 1996. Their work in Everett was followed by site visits to Kawasaki Heavy Industries (KHI) in Japan during January of 1997 and resulted in three unpublished Boeing Proprietary reports (maintained by the MIT Fast and Flexible Manufacturing Project). An effort is made to apply their methodologies and lessons learned to the aft join.

2.3.2 Line Moves

An airplane moves into final body join when a "line move" occurs (during the internship this was every third manufacturing [M] day). The move begins at the end of second shift when factory traffic is low. The synchronization of activities involving large numbers of personnel, cranes, and airplane structures occurring rapidly and safely impresses one that Boeing has military-like competence in these areas.

A completely assembled airplane 'rolls out" of the factory from one of the slant positions (Appendix 4 shows six airplanes in slant positions. Airplanes leave the factory through large bay doors where the numbers 40-25 and 40-26). Jobs scheduled for completion that remain open at the time of a line move become "travelers". These are carried over into downstream workstations until they are closed out. Throughout the manufacturing channel uncompleted jobs normally do not delay a line move because of the ability to "travel" work to the next control code. After leaving the factory airplanes go to paint, fuel, and flight operations.

Roll out of an airplane creates a vacancy in one of the slant positions which is filled by an airplane from an upstream slant position. After several airplanes are moved there is a vacancy for the airplane in final body join to fill. The airplane leaving final body join rolls for the first time into the nearest slant position. FBJ now has room to accept delivery of the landing gear and body structures. These are lifted in place by crane. The center section is located and becomes the monument. Forward and after bodies are lifted in place and laser targets are installed in preparation for joining and alignment of the airplane sections. Vacancies are created upstream in the "back shops" where cranes load panel assemblies to begin the build cycle of the next set of body structures.

2.3.3 The Final Body Join Laser Alignment System

An oft cited success of the 777 program is the fact that aircraft alignment from forward to aft is better than any other airplane in the world. This means that the 777 is straighter from nose to tail than previous generation airplanes. This achievement is attributed to the implementation of Hardware Variability Control (HVC) and the use of a laser alignment system. A detailed discussion of this system is beyond the scope of the thesis but data from it are presented and discussed in Section 5.2.3.

2.4 Airplane Requirements

Top level airplane requirements are identified on a Boeing drawing known as the airplane integration plan (AIP) part of which is shown in Figure 2.1. These requirements include:

Body:

- Straight, level, and round
- Uniform gap circumference at each body joint
- Skin lap horizontal alignment
- Fastener alignment between sections

Wings:

- Dihedral
- Sweep
- Incidence
- Contour, alignment of folding wing

Wing/Body Fairing:

- Uniform gaps fair

Horizontal stabilizer:

- Dihederal
- Sweep

Vertical Fin:

- Normal to section 48

General:

- Uniform gaps, fair of doors

- Frame station values
- Cargo handling system operational
- Interior alignment
- Fit, form, and function of all I/R (interchangeable and replaceable) items

In Figure 2.1 station [STA] is the perpendicular distance in inches from the nose of the airplane to a point aft; waterline [WL] is the vertical distance from ground level in inches; and buttock line [BL] is the distance in inches to the left or right from the airplane centerline. Datums are reference points, lines, or planes from which other locations are measured and indexes are hardware surfaces on either a tool or the airplane from which a part is physically located. Two important considerations in the 777 program were the choice of WL and BL datums. The left buttock line [LBL] 11.00 seat track and WL 200.00 were selected because these datums also serve as indexes from which other parts can be located. This is in contrast to a situation where the datum is a point in space without a corresponding hard surface. In this case part locations would be measured from one point but physically located from another resulting in accumulated variation. The 777 airplane is both measured and built around LBL 11.00 and WL 200.00 which helps to ensure that top level requirements are met. Station indexes and datums depend on the particular airplane section because, unlike LBL 11.00 and WL 200.00, there is no single station line that is common to all sections of the airplane from nose to tail.

Top level requirements necessarily impose requirements on the body structures that make up the airplane. For example, the integrated structure cannot be straight if component body sections are built in such a way that they cannot be joined in a straight line. This fact gives rise to the concept of "flow-down". Top level requirements determine the requirements that must be met by the next lower assembly to ensure that the top level requirement will be satisfied.

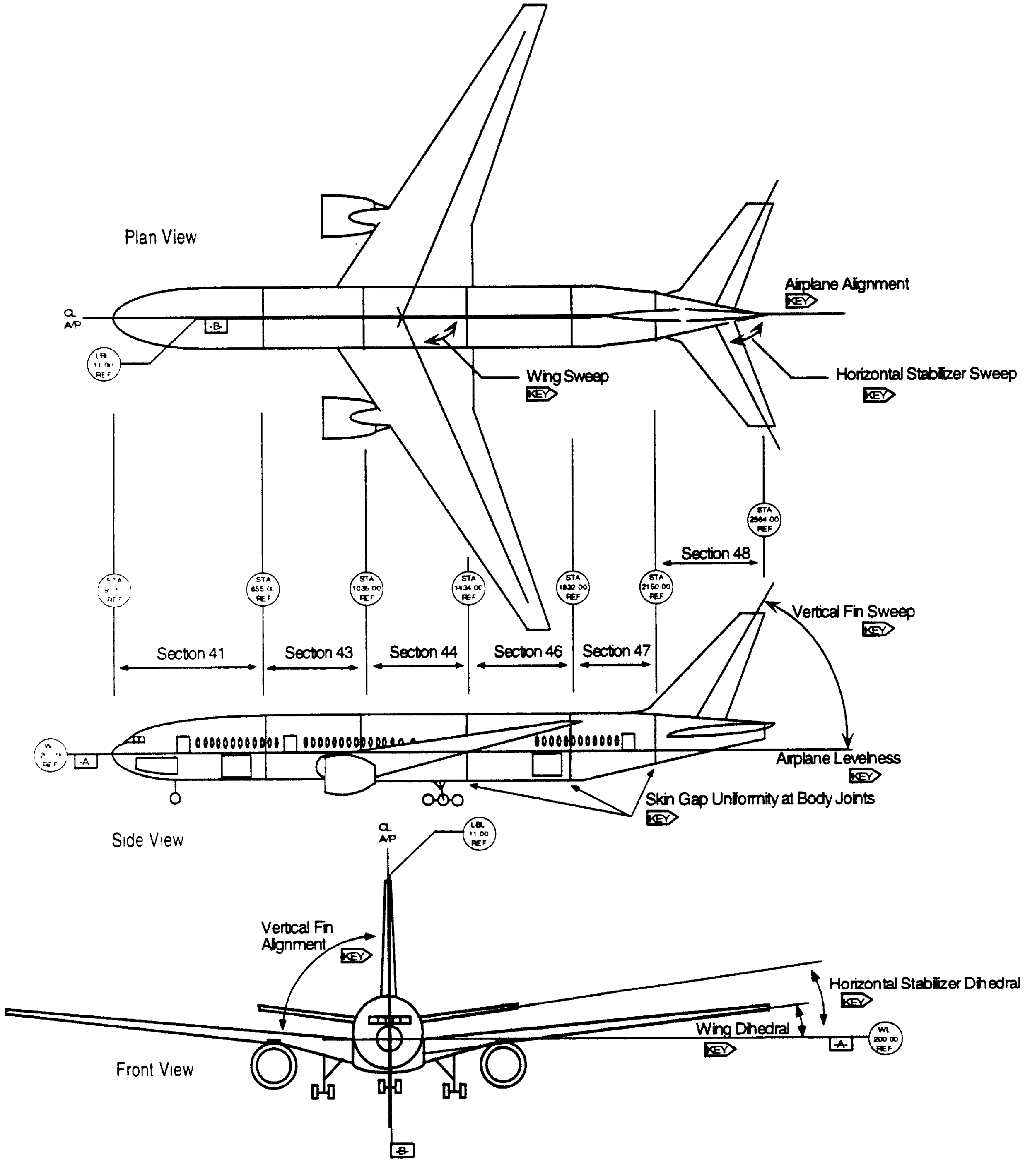

Figure 2.1 Top level airplane requirements

2.4.1 Key Characteristics

Top level airplane requirements determine the key characteristics (KCs) for airplane interface and assembly. KCs are "attributes or features (dimensions or specifications) of a part, assembly, installation, or system in which variation from nominal has the most adverse effect upon fit, performance, or service life[5]". Flowdown of top level requirements establishes KCs for major joins and subassembly builds that occur at FBJ and in backshops, respectively.

Lower level KCs are of two types: those which flow down from a higher, and those which exist for assembly purposes within the given shop. Cunningham and Whitney[6] refer to these as product and assembly KCs (PKCs and AKCs, respectively) and show that the risk of error upon integration of apparently properly made elements can be estimated and, hence, controlled by introducing proper metrics during the product design stage.

2.4.2 Impact of internship on factory performance

A goal of the internship was to complete a project that would have immediate cost, quality, and delivery consequences. The reasons for this approach are best summarized by Edgar Schein who states in his book Organizational Culture and Leadership that "one can understand a system best by trying to change it...culture will not reveal itself that easily and one must actively intervene to determine where stable rituals, espoused values, and basic shared assumptions are located...some of the most important things I learned about cultures [of companies I studied] surfaced only as reactions to my intervention efforts[7]." In part three of the book he gives methods to study and interpret culture and states that when studying culture for the purpose of reporting to outsiders (as is the case here) a very useful approach is to "adopt a clinical perspective, attempt to be helpful to the organization." Further, the process of bringing culture to the surface "requires considerable investment of time and energy on the part of the insider [Boeing employees in this case] and hence is more likely to be successful if the insiders are also attempting to solve their own problems. If the deciphering is done purely as a research process where the outsider attempts to get permission to observe and talk to insiders, she or he will not get the level of cooperation and motivation needed...on the other hand, if the researcher has enough time to

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[5] Hardware Variability Control, Student Manual for Existing Design, Boeing Commercial Airplane Group, 1994.

[6] Cunningham, Timothy W.; Whitney, Daniel E., The Chain Metrics Method for Identifying Integration Risk During Concept Design, submitted to ASME DTM 1998.

[7] Edgar H. Schein describes the clinical research model in his book Organizational Culture and Leadership, page 30.

become an accepted and *helpful* part of the group, the process can work because the insiders will then become motivated to help the researcher.[8]"

It is easy to make recommendations when one is not responsible for carrying them out. Without sensitivity to human and cultural implications, recommendations such as "reduce rework" or "focus on customer satisfaction" are of little value. Given this premise, the value of any suggestions resulting from the internship is enhanced by association with a hands on implementation.

For these reasons the strategy of the internship was to directly impact cost, schedule, and quality and then leverage the lessons learned during the corrective action process into broader generalizations that could be useful in other areas. The next chapter describes the specific problem that was addressed during the internship in order to accomplish this goal.

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[8] Pages 169-171.

3. Chapter 3 - Description of Section 44 Body Panel Excess Length Problem

This chapter begins with a discussion of the section 44 assembly process and associated key characteristics from the vendor to final body join. Following the introductory material is a description of the hardware variability problem that was identified and diagnosed during the internship resulting in a change to the vendor's process.

3.1 Section 44 Assembly Process

This section describes the measurement and assembly processes for section 44, also referred to as the wing center section.

3.1.1 Measurement systems in use

Measurements are taken before, during, and after each assembly stage and fall into one of three broad categories:

- Quality Assurance (QA) measurements - performed by trained and dedicated inspectors. QA requirements are directive in nature. Failure to obtain QA approval on a required inspection generates a non-conformance reject tag (NCR) resulting in a material review board (MRB)[9] and possible rework and production delays.
- Hardware Variability Control (HVC) measurements - performed by shop personnel in conjunction with their other responsibilities. Out of tolerance HVC measurements do not automatically generate rework or MRB as do problems with QA. How seriously HVC measurements are taken, if they are taken at all, depends on the level of Process Engineering interaction with the shop and the perceived value of the measurements to the shop.
- Informal measurements - do not fall into the category of QA or HVC. "Informals" can be taken by anyone who is interested in the information they might provide. The informal measurements are non-directive in nature but can be a powerful tool for process improvement given current shortcomings of HVC.

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[9] See Appendix 6 for definitions.

3.1.2 Key Characteristics for The 44-46 Join Process

Top level requirements of Figure 2.1 are used to determine the KCs for the aft join. These are shown below in Figure 3.1. Seat track station gap was discontinued as an HVC item (L/N 343); QA approval, however, is still required for this feature. Differences between QA and HVC KC requirements are discussed further in Section 5.2.1.

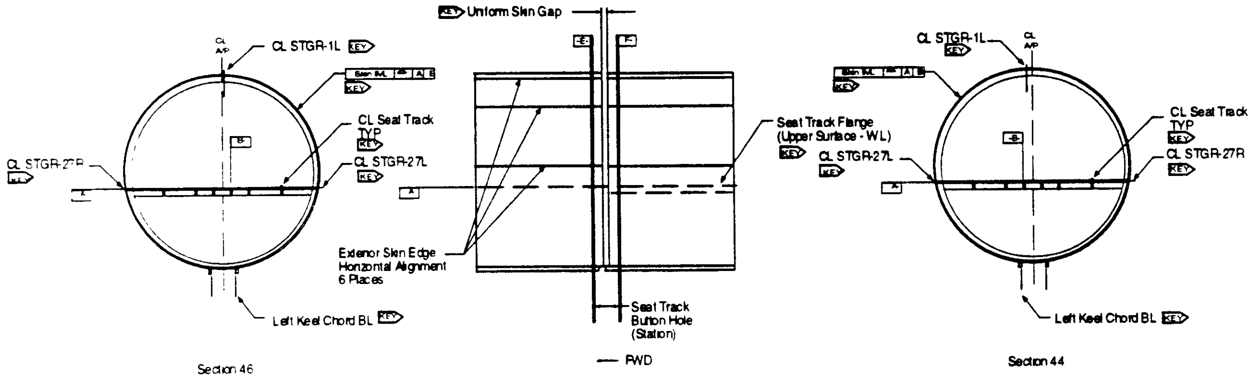

Figure 3.1 Key Characteristics for the aft join

Five HVC KCs are monitored at FBJ (this is true for both the forward and aft joins. Mantripragada and Adams[10] studied the forward join). Six FBJ KCs are listed below but note that the second of these was suspended on airplane number 22:

1. Waterline (WL) 200 alignment (KC.1.131.1) is a top level key characteristic (datum A in Figure 2.1). The WL 200 datum flows down from the AIP to CC131 and to backshops (CC315 for section 41/43; CC325 for section 46; CC328 for section 46/47/48; and CC335 for section 44) to establish and maintain WL throughout the build cycle. Final verification is performed by laser alignment at FBJ (Figure 5.7). Herein is a principle advantage to choosing WL200 as both the primary WL datum and index. All airplane body sections are measured and built to the same common reference plane. When the body sections are aligned in downstream joining operations, other airplane features on the sections are much more likely to also line up due to the common datum and indexing scheme.

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[10] Krish Mantripragada and Jeff Adams, Boeing Trip Report, Massachusetts Institute of Technology, 1996

2. Seat track LBL 11 (KC.1.131.3) was suspended on line number 22. The LBL 11 seat track (datum B in Figure 2.1) is used to build a straight airplane. That is, since LBL 11 is the BL datum and index for the entire airplane, then if LBL 11 is straight, the airplane should also be straight. As with KC.1.131.1, LBL 11 flows down from the AIP to FBJ and to back shops.

   KC.1.131.3 was suspended because of tool problems. Moreover, skin edge and seat track gap best fitting[11] practices were thought to compromise the data in terms of process feedback to build areas. This occurred because QA requirements supercede those imposed by HVC. QA rejection tags are written against non-conforming seat track station gaps and body panel skin gaps, but not for airplane straightness. An out of tolerance condition for gap features results in rework and production delays but slight adjustments in airplane alignment do not. Unless two adjacent body sections are perfect it is not possible to have the airplane exactly straight and also have uniform and even gaps everywhere[12]. If LBL 11 is not straight it might be because the seat track itself is at an angle or because the section is joined at an angle to ensure that all gap tolerances are met. In practice, seat track and skin gaps are used as proxies for airplane straightness and airplane alignment is then checked with the laser alignment system resulting in a "best fit" compromise. Laser alignment is discussed in Section 5.2.3 and BL alignment data are shown in Figure 5.8.

3. Inside skin surface (ISS; KC.1.131.4) is used during body section buildup and does not flow down from the AIP. This KC is used to ensure proper contour integration of the fore and aft stovepipe joints of the fuselage sections (see Mantripragada and Adams, Boeing trip report).
4. Keel beam interface (KC.1.131.5). Keel beam buttock line interface does not flow down from the AIP but is required at FBJ to ensure straightness of the keel and radial (clocking) position of the forward and aft bodies relative to the center section.

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[11] see Appendix 6.

[12] An assembly step that requires control over more attributes than what is physically possible is said to be over-constrained. Over-constrained conditions arise because the location of a given feature on a rigid structure cannot be independently changed without changing the location of other features on the same part. Only a perfect part in a perfect assembly will have all features match exactly.

5. Uniformity of circumferential skin gaps (KC.1.131.7) around the outer perimeter of the airplane at major body joints is a top level KC that flows down to FBJ and the back shops. The measurement is part to part and is also required by QA. These data are discussed and plotted in Chapter 5.
6. Horizontal skin lap alignment (KC.1.131.8) is a top level KC that flows down from the AIP to back shop assembly. Forward and aft fuselage skin laps are measured relative to the center section skin laps.

The internship case study problem (described in Section 3.2) examines KCs affected by excess station length of section 44 body panels. That is, seat track and skin station gaps and corresponding QA and HVC measurements. Because the build plan for section 44 washes variation to the aft station, we are concerned primarily with the aft join.

3.1.1.1 Operational necessities and cultural implications

Mantripragada and Adams noted that the FBJ KCs are tightly coupled and cannot all be independently controlled. This suggests that there is a physical explanation for why "best fitting" occurs: operators are forced to decide between two alternatives that are mutually exclusive. This is true throughout the manufacturing channel including the shops that build the body sections that are joined in FBJ. In order to satisfy QA, backshops must wash variation into non-QA areas if they wish to make rate. FBJ in turn must also satisfy both QA and production rate requirements and therefore washes hardware variation into airplane straightness because this characteristic does not generate QA rejection tags. The absence of reject tag activity is interpreted by the backshop as a signal that there is no problem.

Operational personnel are forced to develop a standard for prioritizing mutually exclusive requirements. The recurring theme throughout the factory is:

1. Satisfy QA requirements
2. Make production rate
3. Minimize non-MRB shimming
4. Satisfy internal customers and HVC requirements

The accepted norm, which is to wash variation into non-QA areas, seems to have evolved out of operational necessity. People were asked to do something impossible and did their best to deliver.

3.1.2 Section 44 build process and Key Characteristics

Section 44 is assembled in CC335 in one of two Floor Assembly Jigs (FAJ 144W0000) at the Everett facility. There are two FAJs side by side. Odd numbered airplanes are assembled in FAJ 1 and even numbered airplanes (including all of the 777-300s) in FAJ 2. The major components and steps depicted in Figure 3.2 are:

1. Load the 11/45 section
2. Load and index the aft wheel well side of body (SOB) fittings (pickle forks)
3. Load and index the rear spar SOB fittings
4. Load and index the front spar SOB fittings
5. Load and index the left side panel
6. Load and index the right side panel
7. Load and index the crown panel

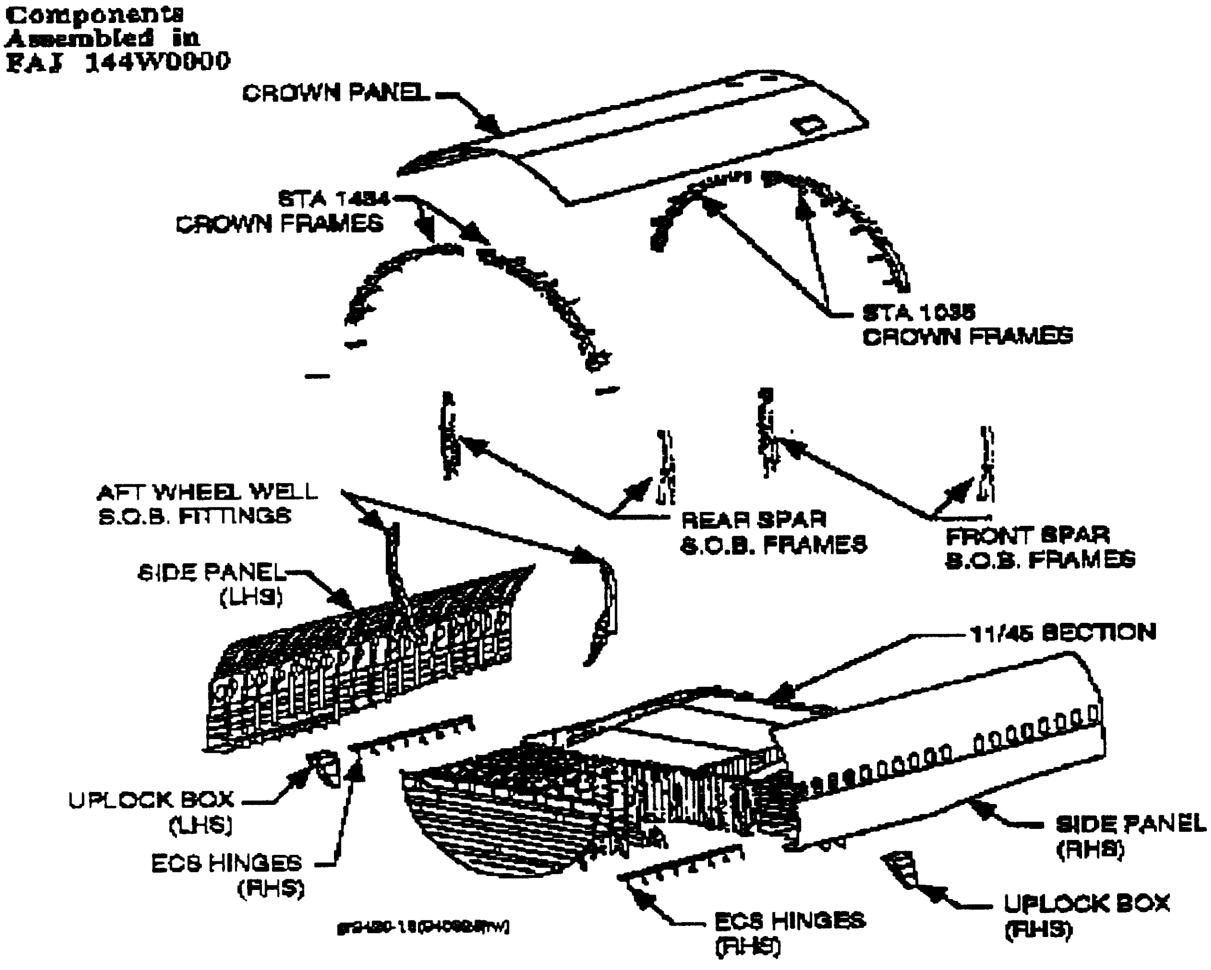

Figure 3.2 Section 44 major components assembled in CC335

Datums and Key Characteristics for the section 44 assembly are shown in Figure 3.3. The 11/45 assembly is craned into position on six hydraulic jacks which are set to nominal. Level is checked at three station locations at L/R BL 96 and WL 200 using a laser tracking system. Based on discussions with shop mechanics the check is usually satisfactory and when it is not tooling or target positioning can be corrected to achieve nominal leveling. Thus the locations of key datums are determined by the accuracy of the vendor build process for section 11/45 and the ability of the jacking system to place the section at nominal position within the FAJ coordinate system. All other components are indexed to locations on the FAJ. Thus, in the as-designed build process, part dimensions and FAJ features jointly determine the accuracy of the final assembly.

Seat track stations are set by the assembly vendor Fuji Heavy Industries (FHI). The vendor indexes forward section seat tracks from the forward station and aft seat tracks from the aft station so that variation is washed to the interface in the center of section 44 rather than to the final body join datums D and E shown in Figure 3.3. This results in a critical interface in the center of section 44 but less variation in seat track station gap at final body join. The original build plan at CC335 called for the measurement of LBL 11 station deviation at STA 1035.25 and 1433.5 but this check has not been performed. Data from FHI for seat track station is up to date and shows tight control. These data are not included in this report.

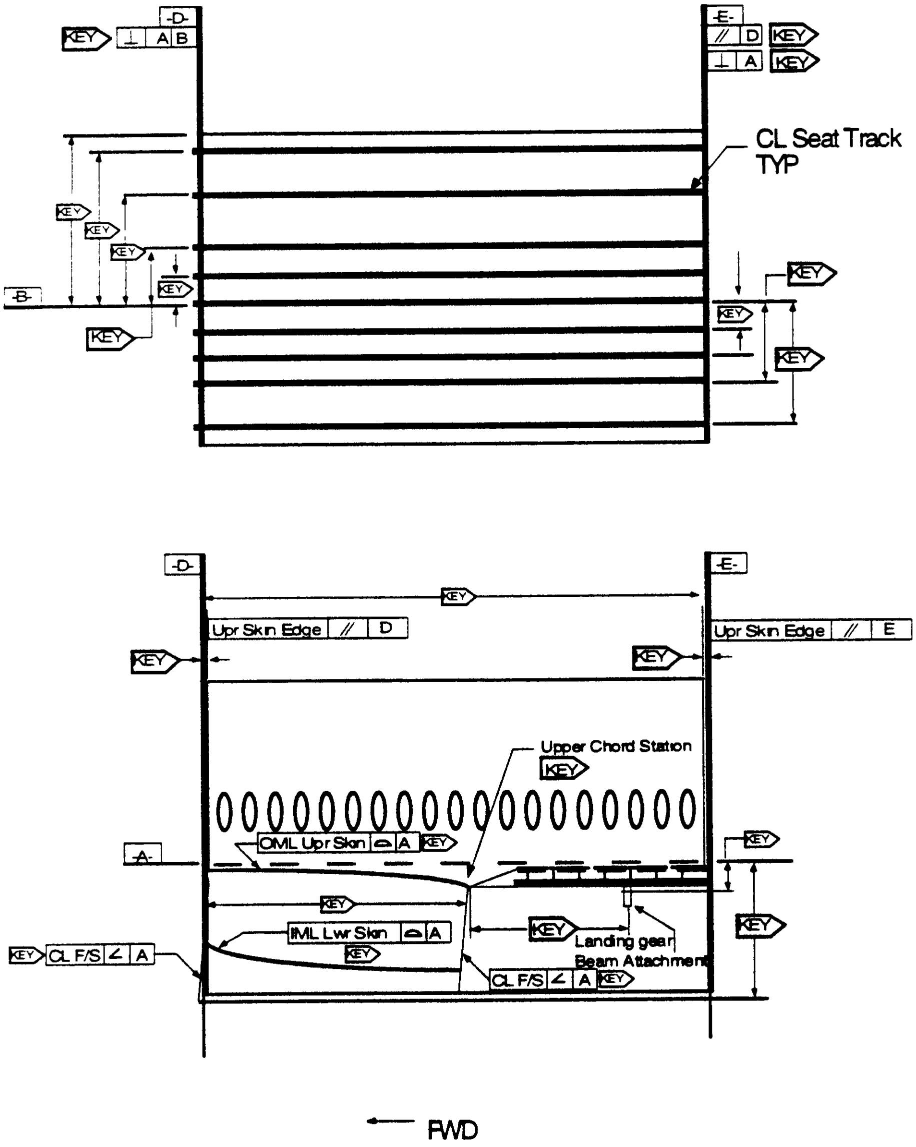

Figure 3.3 Section 44 Datums and Key Characteristics

3.1.4 Vendor Key Characteristics for section 44 body panels

Of interest in the baseline case study is the location of the section 44 body panel aft skin edge and the factors that affect it. Side panels are received from KHI at net trim and indexed in CC335 at stringers 19L and 19R. Crown panels are indexed at stringer 12L and 12R to features on the forward end gate of the CC335 FAJ. All panel length variation is therefore washed aft to station 1434. CC335 mechanics do not directly control the location of the aft skin edge; it is taken as given.

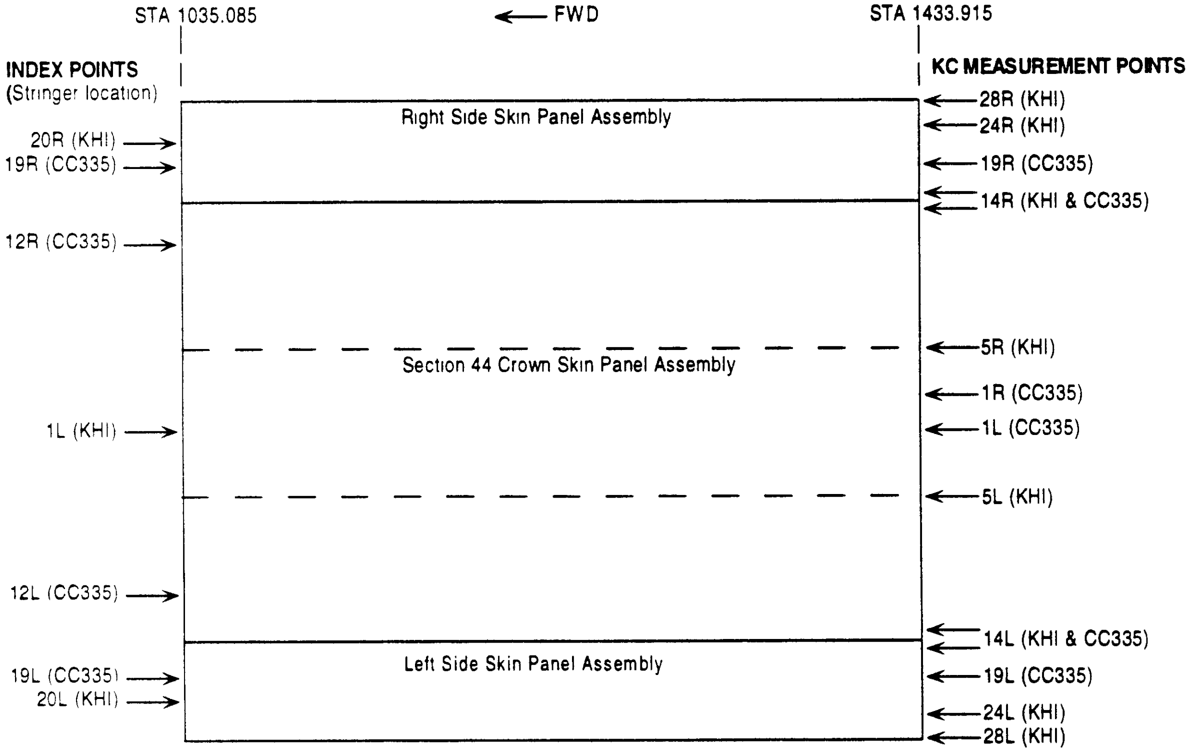

Figure 3.4 Section 44 body panel station index and measurement points.

Figure 3.4 shows the locations of section 44 body panel index and KC measurement points at KHI and CC335. Unlike CC335 which builds airplanes in two FAJs, KHI assembles section 44 body panels in respective single FAJs. Measurements are not taken at the forward end (STA 1035.25) because this is the primary station index (section 4.3.1 discusses this fact in greater detail which stems from the assumption that the existence of a hard index determines the exact location of a part so that measurement is not necessary). The arrows on the left side of Figure 3.4 pointing to the skin edge at STA 1035 represent the stringer locations of hard index points at KHI and CC335. KCs for aft skin edge station are measured at the stringer locations shown on the right side of Figure 3.4. For example, at KHI the forward edge of the right side skin panel assembly is indexed at stringer 20R and the aft skin edge station location is measured at stringers 28R, 24R, and 14R. CC335 indexes the same panel at stringer 19R and measures aft skin edge station location at stringers 19R and 14R.

Figure 3.4 reveals that:

- Many index and measurement points for KHI and Boeing do not coincide.
- The aft skin edge station location is determined by the location of the forward skin edge and the length of the panel. CC335 receives section 44 body panels at net trim and indexes them to FAJ features that are set and checked by a different organization known as "tooling". CC335 therefore has no control over the aft skin edge station location according to the design build plan.

  This design build process creates a dynamic that the author observed in several areas of the factory: Operators believe that they have no control over the area that absorbs process variation [aft skin edge]. If the feature [aft skin edge] is mis-located, there is nothing they can do to correct it and, furthermore [they reason], it is not their fault. There is an HVC KC check (Figure 3.4) but no QA requirement and HVC lacks teeth in that nothing happens if the HVC measurement is out of tolerance or not performed at all. After a while, operators conclude that there is no reason to check the feature. It is simply taken as given. When the shop finds it necessary to deviate from the design build plan (see Section 3.1.5), they do not make a corresponding adjustment to their apriori conclusion that it is unnecessary to check the area where variation is absorbed [aft skin edge]. A problem arises if a downstream shop has a critical interface in this area (such as the FBJ aft join) and the unplanned variation due to shop "best fitting" adds to existing "planned" variation. One possible solution to this dilemma is to flow QA requirements in a fashion similar to that of HVC. Alternatively, as is being done in some areas through Process Engineering efforts, eliminate unnecessary HVC measurements and educate shop personnel on the importance of the KC measurements that are retained.

- No measurements are taken at the forward skin edge. Therefore, compromise of the indexing plan is quantifiable only as variation in aft skin edge station.

3.1.5 As designed versus as built body panel indexing

In practice CC335 mechanics "best fit" body panels contrary to the design indexing scheme (and the directive build plan FAJ 144W0000 sheet 902 page 31-34) to avoid floor beam and frame non-conformance reject activity. Instead of indexing side panels from the forward skin edge at stringer 19L and 19R and crown panels at stringer 12L and 12R, mechanics slide the panels forward and aft to minimize the station mismatch between side panels and center stub floor beam attachment points and between crown and side panel frame ends. The center stub transverse floor beams attach to seven locations in the lower aft area of the side panels although this is difficult to see in Figure 3.2. Best fitting does not always cause a problem (nor is it avoidable given the over-constrained nature of the design build plan [see Chapter 6 for the datum flow chain analysis]). If it is necessary to "best fit", however, it should be done with a knowledge of who might be affected downstream.

"Best fitting" can either alleviate or aggravate the effect of accumulated variation at the aft skin edge and CC335 should therefore include appropriate process checks when they are forced to knowingly violate the build plan. For example, if a crown panel is slightly longer than the nominal engineering dimension (398.830 inches) the length variation has less impact on the aft join if the panel is moved forward slightly during section 44 assembly. On the contrary if the panel is moved aft this effect combines with the excess length to worsen the condition of the aft join.

As in the case of final body discussed above, mechanics in CC335 have informally developed a prioritization scheme that allows them to manage the requirements to build an over-constrained assembly. The priority sequence established by the shop calls for:

1. Match floor beams so as to minimize shimming requirements (NCR required if station mismatch is greater than 0.063).

2. Match crown to side panel frames so as to minimize shimming requirements (NCR required if frame station mismatch is greater than 0.056).
3. Index forward skin edge of body panels to within +/- 0.030 of nominal.

The basis for the informal prioritization scheme is to first minimize QA reject tags which result in production delays and rework. Variation in floor beam and frame station location is washed to skin edges which in turn feeds into airplane alignment as discussed in Section 3.1.2. The forward skin edge is checked to ensure it is not greater than 0.030 inches from the index point and aft skin edge is taken as given. In Chapter 6 datum flow chain (DFC) methodology is used to show that the design build plan for section 44 crown and side panels is not statistically capable of matching frames to within 0.056 for station.

3.2 777 Hardware Variability Corrective Action: Baseline case study

This section describes a problem for which supervisory personnel in final body join were eager to receive Process Engineering support. It became the basis for the internship case study because it could be completed within six months and had significant cost, quality, and delivery consequences.

3.2.1 Problem Description and Definition

The problem situation occurred in the aft join of FBJ where the forward end of section 46 is joined to the aft end of section 44. Section 44 crown panels protruded aft beyond the side panel assembly skin edge by 0.030 to 0.120 inches. This condition complicated the aft join due to:

- tight crown skin gap between 44 and 46 sections.
- non uniform circumferential skin gap around the aft join due to crown to side panel misfair[13].
- wide seat track station gap due to crown skin reaching lower specification limit before seat track gaps were in tolerance.
- short edge margin on the 46 section keel panel assembly.

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[13] Misfair is the effect of variation on panel length and position. Two edges that are designed to be flush are slightly displaced relative to one another. A diagram of this condition is shown in Figure 3.6.

Engineering requirements for section 44 panel assemblies call for skin station location to be within 0.040 inches of nominal. Therefore the maximum amount of misfair between the crown and the adjacent side panel that could result from properly indexed in tolerance skin panels is 0.080 inches. Final body join QA inspection records indicated that crown to side panel misfairs as large as 0.120 inches had occurred and that on average the misfair was about 0.050 inches. The result of this condition was that the aft join had a skin gap at the crown that was smaller than the nominal value and a seat track gap wider than nominal.

This is represented on the diagram in Figure 3.5 which shows nominal (left) and as-is (right) joins for the characteristics of concern final body join[14]. The dashed line represents STA 1434 about which the aft join is nominally centered. In the nominal join, which is shown on the left side, the crown and side panels have a uniform skin gap of 0.170 inches with a tolerance of +/- 0.080 and the seat tracks have a gap of 2.00 +/- 0.060. In the keel area the section 46 keel panel must fit over the section 44 strap so that a standard drill jig can be used to locate rivet holes prior to fastening the two sections together. The rivet holes must be drilled at least one diameter away from the edge of the section 46 keel skin and also one diameter away from the edge of the section 44 strap. If a hole is located such that if it is drilled there will be less than one hole diameter of metal between the edge of the part and the hole, a condition known as a short edge margin will result. A short edge margin is of serious concern because there is insufficient metal between the fastener and the edge of the part to ensure sufficient structural strength is maintained. To prevent a short edge margin the drill jig must be manually located. This results in production delays and an increased risk of mislocated holes which must be filled and re-drilled causing further delays.

On the right side of Figure 3.5 is depicted the condition of a typical join. The gap between the body panels is tighter than nominal and the section 44 body panels appear closer to the dashed line that represents station 1434. Also, the crown panel is misfaired aft relative to the side panels. At the same time the seat track gaps are wider than nominal and there is a frequent occurrence of short edge margin at the keel.

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[14] I thank Process Engineer D. Watters for the descriptive picture. Contributions from he and co-worker C. Schweigert appear throughout this thesis. Any omission of specific reference to their work is unintentional.

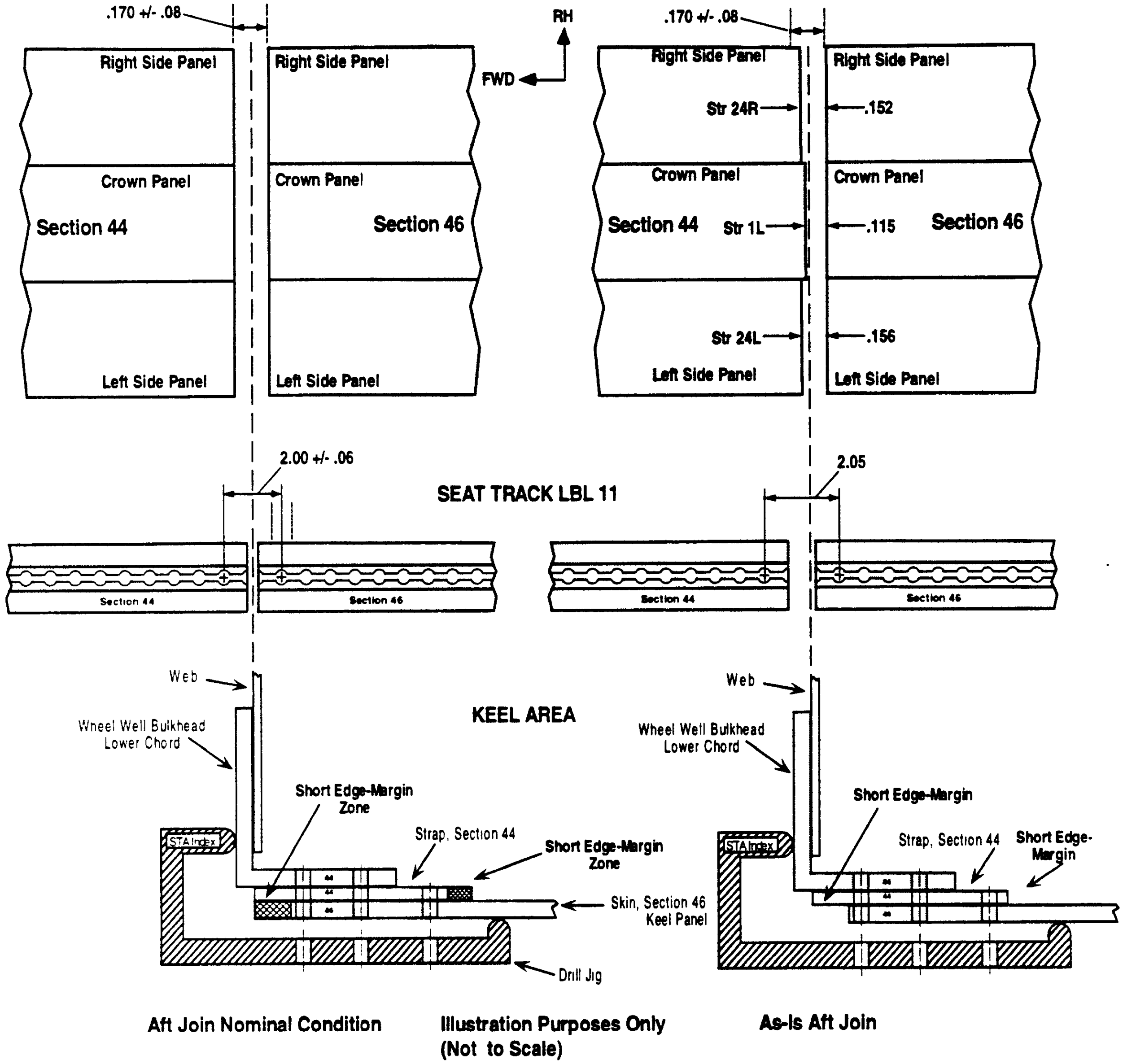

Figure 3.5 Comparison between nominal and typical aft joins

There are many explanations of how such a condition could result because the fit between section 44 and section 46 depends on features of both sections. One hypothesis is that section 44 body panels are longer than nominal. If this is true the skin gaps would be expected to close to the lower tolerance limit before the seat tracks and keel edges reach their nominal positions. This is exactly what is shown in the as-is join on the right side of Figure 3.5.

3.2.1.1 Recent Events

Non conformance reject tags were written on airplanes in June of 1997 (L/N 351) and September 1997 (L/N 377) both of which precipitated trimming rework in FBJ (see 3.2.2.1 for problem chronology through June 1997). The activity in September of 1997 resulted in the loss of one [M] day of production. Process engineers Schweigert and Watters prepared the visual description of the situation as it appeared in September 1997. This is shown in Figures 3.6 and 3.7.

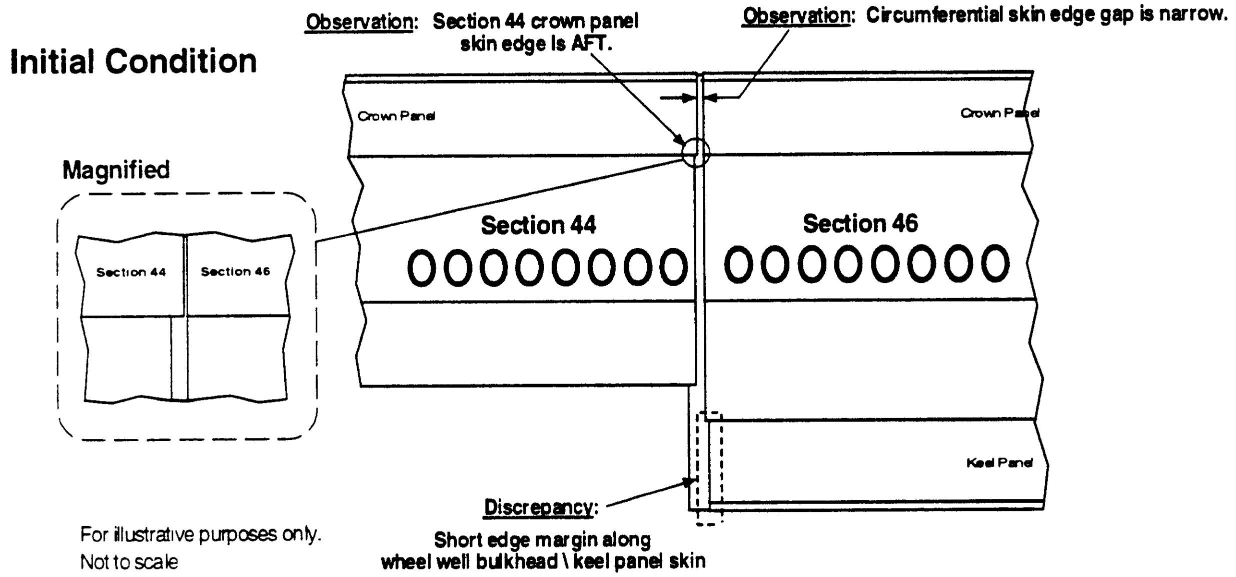

Figure 3.6 Initial condition of aft join in September 1997 event

During the June 1997 rework it was noted that there was considerable risk of damage to the crown ring which is flush beneath the aft skin edge of section 44 (see the STA 1434 crown frames in Figure 3.2). Accordingly, in the September 1997 event the aft join was separated and the section 46 forward skin edge was trimmed to remove the interference. This is illustrated in Figure 3.7.

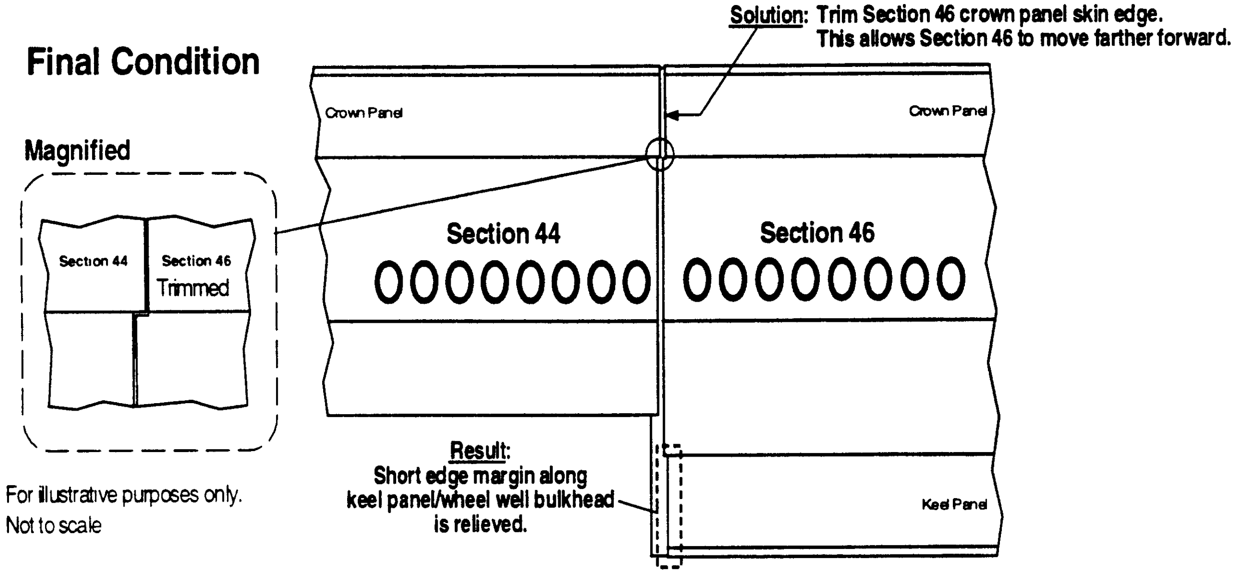

Figure 3.7 Rework to correct section 44 aft crown skin protrusion in September 1997

Following the September event in final body join there was significant management emphasis to perform rework before body sections arrived at final body join. (FBJ is an historic bottleneck. Lost output from FBJ is lost to the entire factory but the extent to which final body join was a bottleneck had been significantly reduced in the past year due to improvements in the forward join).

Preemptive rework on section 44 aft skin edges had already been performed on two airplanes in July of 1997 in anticipation of potential interference problems in final body join because the crown to side panel misfair was so pronounced that it could not be ignored by the build shop (CC335). The rework, however, was unsatisfactory from the standpoint of final body join because CC335 only trimmed the crown aft skin edge at the lap where the part to part fit between the crown and side panel could be readily observed. This made it appear as though the crown and side panels were flush. When these airplanes were joined, however, the crown protrusion caused interference problems in areas away from the laps where no trimming was performed. Sophisticated upstream rework was initiated by Schweigert and Watters on airplanes subsequent to the September event. In these cases a clean station line was cut from the aft end of the section 44 crown if measurements indicated that an interference condition would occur in final body join.

Airplane alignment was often adjusted in order to absorb the crown panel aft protrusion rather than trimming. The tail of the airplane was deflected slightly downward to widen the skin gap at the crown, close the seat track station gaps, and improve the edge margin at the keel. Compromising airplane alignment to ameliorate a panel excess length problem may appear to be questionable judgement yet it is rational from the perspective of the join crew:

- the assembly is over-constrained and it is not possible to have both a straight airplane and gaps that are within QA tolerance limits because of the variation in the body structure hardware features.
- there is considerable emphasis on maintaining the scheduled production rate.
- to correct the body structures so that the airplane can be nominally aligned and gain QA approval for gaps would require rework and production delays.
- prevailing cultural folklore states that if features of the airplane (skin gap and seat track station gap) are satisfactory to gain QA approval any impact on airplane alignment will be insignificant with respect to drag penalty (this is discussed in Section 5.2.3).
- there is no QA requirement for airplane alignment.
- no higher level directive guidance is given as to which of the mutually exclusive alternatives is most important.

Recall that the line move occurs on third shift. The operators are forced to use their judgement and experience to decide what is most important. Features that require QA approval are reasonably assumed to be critical as is production rate. It is a logical conclusion that alignment is not as important. Moreover, small adjustments to gain QA approval are thought to be insignificant. Laser alignment data for airplane straightness, the effect of adjusting airplane alignment to control skin and seat track station gap, and aerodynamic studies are presented in Section 5.2.3.

3.2.1.1 Problem History

The following chronology is not intended to be comprehensive but rather to demonstrate that the join performance experienced during the internship period did not suddenly begin in June of 1997 but was the result of a bias rooted in the inception of the 777 program. Comments pertain to the section 44 aft end (STA 1434) and were obtained from final body join QA records. There were no comments regarding airplane alignment or panel misfair at the forward end of section 44 through June of 1997.

Date	**Comments**
July 1993	First 777 is joined
June 1994	FBJ QA data is available
April 1995	QA notes left side panel shifted forward relative to crown
April 1995	QA notes crown panel misfaired aft 0.080 relative to sides
Feb 1996	QA notes misfair between crown and side panel at stringer 14L
July 1996	Non-conformance reject (NCR) activity for 44/46 keel short edge margin
Oct 1996	short edge margin
Jan 1997	QA notes difficulty satisfying skin and seat track station gaps
Mar 1997	short edge margin
April 1997	short edge margin
April 1997	QA notes tight skin gaps and short edge margin
April 1997	short edge margin
April 1997	short edge margin
April 1997	QA notes crown misfaired 0.070 aft relative to sides and short edge margin
April 1997	QA notes crown misfaired 0.060 aft relative to sides and short edge margin
May 1997	QA notes crown misfaired 0.080 aft relative to sides and short edge margin
May 1997	QA notes crown misfaired 0.090 aft relative to sides and short edge margin
May 1997	QA notes crown misfaired 0.040 aft relative to sides
May 1997	QA notes crown misfaired 0.040 aft relative to sides and short edge margin
June 1997	QA notes crown misfaired 0.060 aft relative to side at 14L
June 1997	QA notes crown misfaired 0.040 aft relative to sides and short edge margin
June 1997	QA notes crown misfaired 0.050 aft at 14R and short edge margin
June 1997	QA notes crown misfaired 0.080 aft relative to sides and short edge margin
June 1997	QA notes crown misfaired 0.100 aft relative to sides and short edge margin, section 44 crown trimmed in final body join.

4. Chapter 4 - Diagnosis of Problem Using in-place HVC and KC Data

This chapter presents a formal analysis of the subject problem using in-place measurement systems. It shows that variation due to temperature changes in the factory may be a source of significant variation and that measurement systems between KHI and Boeing are inconsistent.

4.1 Introduction

The salient indication noted by final body join QA personnel was that the section 44 crown panel was often misfaired relative to the sides. The condition was confined to the aft end without a corresponding misfair at the front. The analysis begins with a study of existing HVC data and ends inconclusively because of discrepancies between the KHI and Boeing KC data sets. The fact that in place measurement systems were inadequate to help pinpoint the source of the problem is an important lesson resulting from the study.

4.2 Identification of problem

That the problem was identified so far downstream in the manufacturing process (i.e. in final body join instead of in CC335 or KHI) is disturbing in light of the well developed datum flowdown and measurement and indexing plans discussed in Chapter 3. It is also noteworthy that the problem did not receive attention until almost four years of production had elapsed. This may be because there were more important assembly issues competing for limited resource attention, production rate effects that worsened the problem from one of being a nuisance to one of intolerability, or other factors.

From an organizational dynamics standpoint, however, there may be incentives to knowingly pass variation to customers who are likewise incited to wash the variation into different areas (areas not checked by QA) and so on. Customers, on the other hand, have incentives not to initiate formal feedback to the supplier which entrenches the status-quo until it is accepted without question. This occurs because in order to initiate formal corrective action a non-conformance reject tag (NCR) is required. When a shop writes an NCR, however, it often experiences production delays[15] and incurs rework to correct the condition. If a small adjustment can be made (such as shifting a panel forward or aft by 0.030 inches or slightly lowering the tail of an airplane in final body join) to avoid the NCR process, shops often prefer to do so.

4.3 Formal Diagnosis using HVC data

The formal diagnosis is presented in the sequence that parts are manufactured and assembled (during the internship the analysis proceeded from the point of problem identification in FBJ upstream to the first supplier (CC335) and then to Boeing's supplier (KHI)). Data are presented in chronological sequence but airplane line numbers have been disguised.

4.3.1 UMED 40

Technical guidance for the 777 HVC program is given in the Boeing document UMED 40 which directs that KC data be measured at the locations shown in Figure 3.4. Concerning the station position of section 44 body panels UMED 40 makes the following statements:

- "These key characteristics (i.e. the measurement points shown in Figure 3.4) are to be used to maintain circumferential skin gaps at final body join. This is a customer requirement which reflects manufacturing craftsmanship.
- Circumferential skin edges between major body sections must be parallel.
- Measurements are not made at the front of the section due to primary index points. Any growth will occur in the aft direction.
- Station location of the circumferential skin edge must be maintained between the crown panel assembly and the side panel assemblies. Any mismatch between these assemblies will

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[15] Recall that anything requiring corrective action is reviewed by QA, Engineering, and Manufacturing in a formal process. This is considered necessary to ensure that the product is not compromised in any respect. The advantage to this system is that it is a standard and documented process. The disadvantage is that it can take several days for a shop to receive engineering disposition. Given the heavy emphasis on schedule adherence, many consider the MRB process is onerous. In terms of suitability for statistical trend analysis from which root cause solutions can be derived, the author found that the NCR system left much to be desired. Answers to simple questions such as "which airplanes had a keel short edge margin" are almost impossible to find. Consequently, when a problem becomes persistent or bad enough to get attention, the data gathering process must often begin from scratch.

result in a trimming requirement at the aft end of the skin panels. Trimming is to be avoided due to possible damage to the wheel well bulkhead upper frame doubler during the trimming operation in CC335."

4.3.2 Variation due to temperature fluctuations

Boeing receives section 44 body panels from KHI in shipping mechanical equipment (SME) fixtures. Each super-panel assembly (i.e. left, right, and crown) is securely packed in a dedicated SME. SMEs for section 44 arrive in the Everett factory within 24 hours of the panels being loaded in the FAJ although the lead-time varies considerably. This gives rise to the question of thermal expansion and contraction as a potential source of variation.

It is implicitly assumed in the assembly plant that by the time panels are indexed they are in thermal equilibrium with their surroundings and that factory ambient temperature is fairly constant (the author observed that temperature averaged about 75 +/- 3 °F during the internship and that within a given 24 hour period it remained within about a +/- 1 °F range). This is generally a good assumption because of the time the panels spend on the floor and the two to four shifts that elapse between the time when panels are loaded to when they are indexed. It is of course possible that there are times when thermal equilibration has not occurred before indexing and in these instances temperature effects could be a source of variation. This can be shown as follows:

Data	Equation
Thermal expansion coefficient of Al: $\alpha_L = 1.2 \times 10^{-5}$ in/in°F	$\Delta L = \alpha_L \times L \times \Delta T$

Temperature change = 1 °F

Panel length = 398.830 in

$\Delta L = 1.2 \times 10^{-5}$ in/in°F x 1°F x 398.830in = 0.005 inches

For each Fahrenheit degree change in panel temperature the panel length is expected to change by 0.005 inches resulting in a change of about 0.030 inches for the range of temperatures observed in the factory during the internship. Boeing production engineers do not take temperature effects into consideration when assessing sources of dimensional variation. The simple calculation above indicates that this may be a mistake and that better thermal compensation methods could represent an area of opportunity for process improvement.

4.3.3 Vendor KC Data

KHI manufactures section 44 body panel subassemblies at Gifu and performs super-panel integration, skin trim, and measurement at Seaside (see Chapter 6). After trimming the aft skin edge KHI measures KC data relative to the tool. Nominal offset is 0.250 inches which corresponds to an engineering nominal length of 398.830 inches. Values greater than the nominal offset of 0.250 indicate that the panel aft skin edge is farther away from the aft end gate and hence the panel is shorter than engineering nominal. Likewise, if the measurement is less than 0.250 the panel is longer than engineering nominal because the aft skin edge is closer to the aft end gate than the nominal 0.250 measurement offset.

Measurements in Everett are relative to nominal at zero with negative measurements corresponding to a panel length shorter than nominal (i.e. less than 398.830) by the measured amount and positive measurements are longer than nominal. During the internship it was clear that few Everett line engineers understood KHI's measurement system or how to interpret KHI's data. It was not until about the fifth month of the internship that the author deciphered KHI's reporting convention when KHI detailed how proposed trimming changes to section 44 panel length would affect the KC.

KHI was chronically delinquent in submitting KC data. Efforts to obtain overdue data using established channels in Everett proved time consuming and frustrating. For example, L/N 364 was measured by KHI on 3/18/97, assembled by CC335 in June 1997, and joined and rolled out in July 1997. From June to August 1997 attempts were made to obtain KHI KC data for airplanes subsequent to L/N 363. Finally on 9/2/97 data for L/N 364 through L/N 378 were obtained from KHI via paper copy. At the time data through L/N 378 were rendered, however, KHI had already cut and measured up to L/N 393 and CC335 was building L/N 380. Efforts to obtain real time KC data were futile. In mid November data through L/N 404, which had been measured by KHI one month earlier, were received.

The author believes that KHI's delay in providing KC data is significant for reasons beyond mere alacrity. Data trends show that KC.5.KHI.7 had no correlation with Everett measurements up to L/N 378 and then started to agree more closely afterward. This may indicate that KHI discovered errors in their KC measurement process and corrected them but never revealed this fact to Boeing.

KHI data in this section are converted to the standard used in Everett (zero equals nominal and negative sign indicates panel is short). Appendix 5 shows a sample of raw KHI data as extracted from the Everett database. The reporting format does not lend itself to ease of analysis. To perform a meaningful analysis the data must first be sorted by measurement point ID (second column in Appendix 5 which corresponds to stringer location). Data are then converted from airplane effectivity number (i.e. WA001, WB076, etc.) to line number, and finally formatted into a spreadsheet that can be plotted as a control chart. Then 0.250 is subtracted from each KHI KC measurement to convert to the Everett standard. All data in this section were "treated" this way except that line numbers are disguised.

4.3.3.1 Analysis of vendor part to tool KC data

Figure 4.1 shows a summary of treated vendor data for the ten KC measurement points given in Appendix 5. Several conclusions are drawn:

- Ten points measured on over one hundred and thirty one airplanes are difficult to analyze on a single plot.
- Only one point of 1310 is outside of engineering tolerance.
- The data do not explain how crown to side panel misfairs as large as those observed by final body join could occur (FBJ observed up to 0.120 inch differences, see Section 3.2.1).

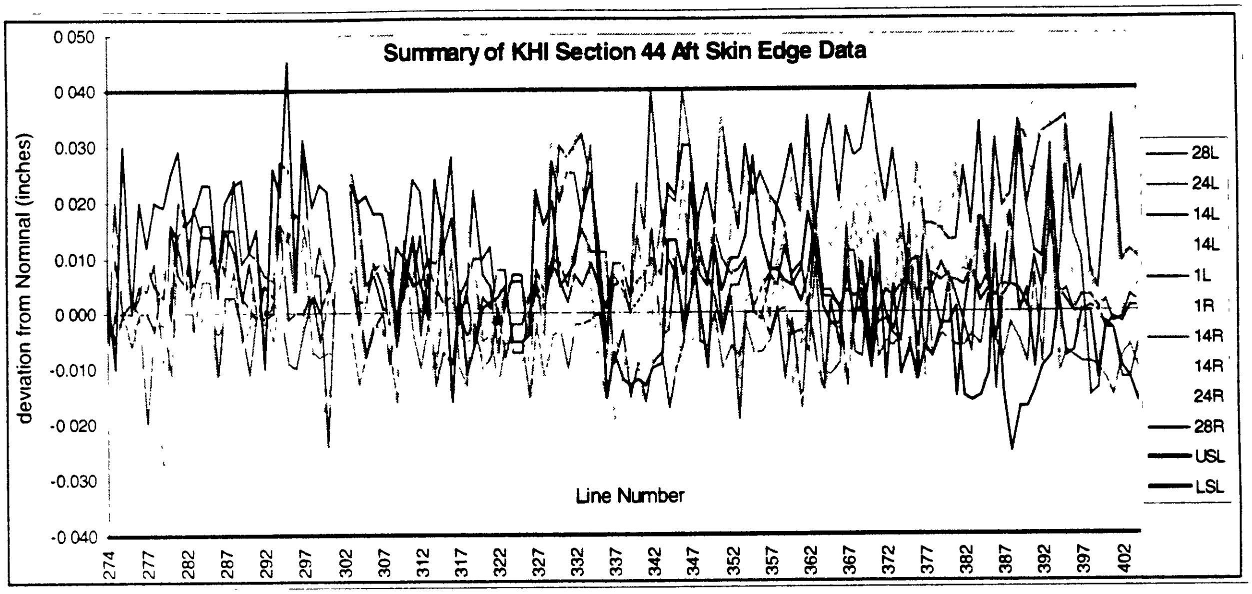

Figure 4.1 Summary of KHI KC measurements on section 44 aft skin edge

The data can be separated into the component body panel measurements for the left side (Figure 4.2), crown (Figure 4.3) and right side (Figure 4.4). This makes it easier to identify trends but it is difficult to perform interpretation that can be directly applied to final body join because FBJ observes the part to part relationship at the aft skin edge at stringers 14L and 14R with crowns misfaired aft relative to the sides. One can conclude, however, from the specification limits and general appearance of the plots, that the vendor data seem to indicate that KHI is not the source of the problems experienced by final body join. The following additional observations are made:

Left Side Panel

- No out of tolerance points.
- Centered around nominal.
- No aberrant trends present.

Crown Panel

- No out of tolerance points.
- Center of crown (1L and 1R) appears slightly longer than laps (14L and 14R).
- Process shift toward longer panels begins around L/N 343 reflected at 1L and 1R.
- Process shift to longer measurement at 14L and 14R begins around L/N 378.

Right Side Panel

- A single point is out of tolerance.
- The process shows a trend to shorter panels beginning around L/N 343.

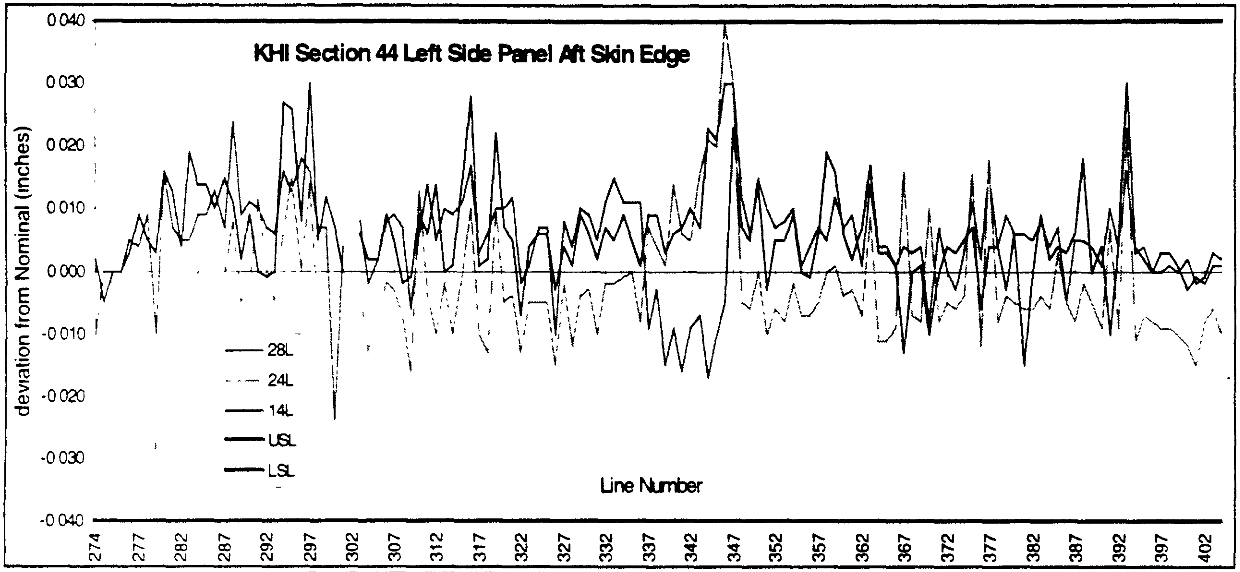

Figure 4.2 KHI KC measurements on section 44 left side panel aft skin edge

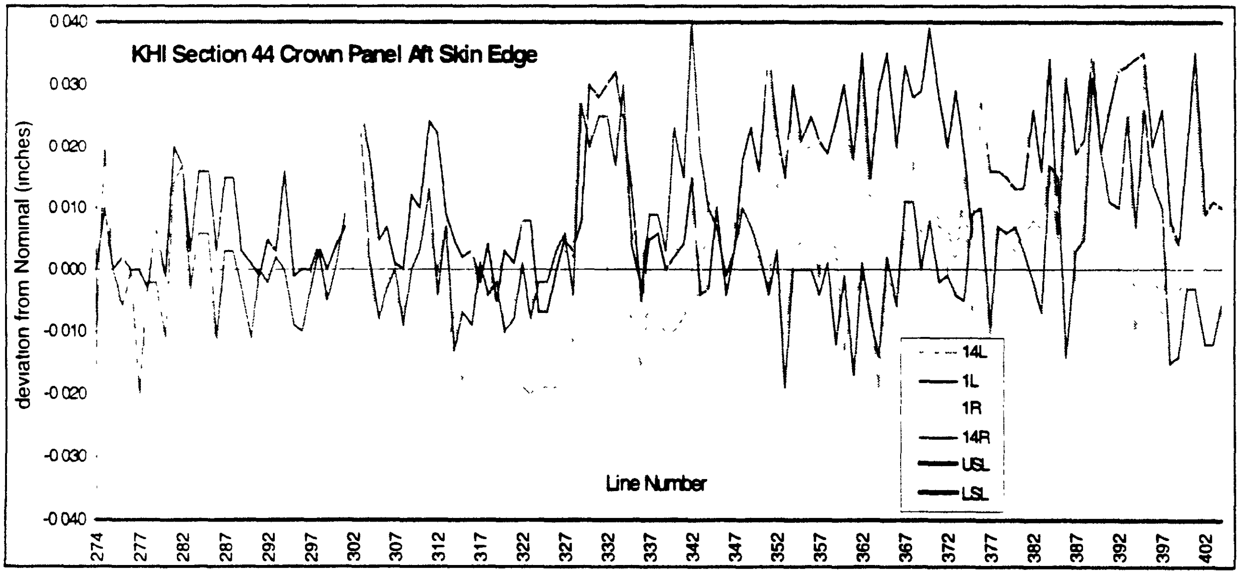

Figure 4.3 KHI KC measurements on section 44 crown panel aft skin edge

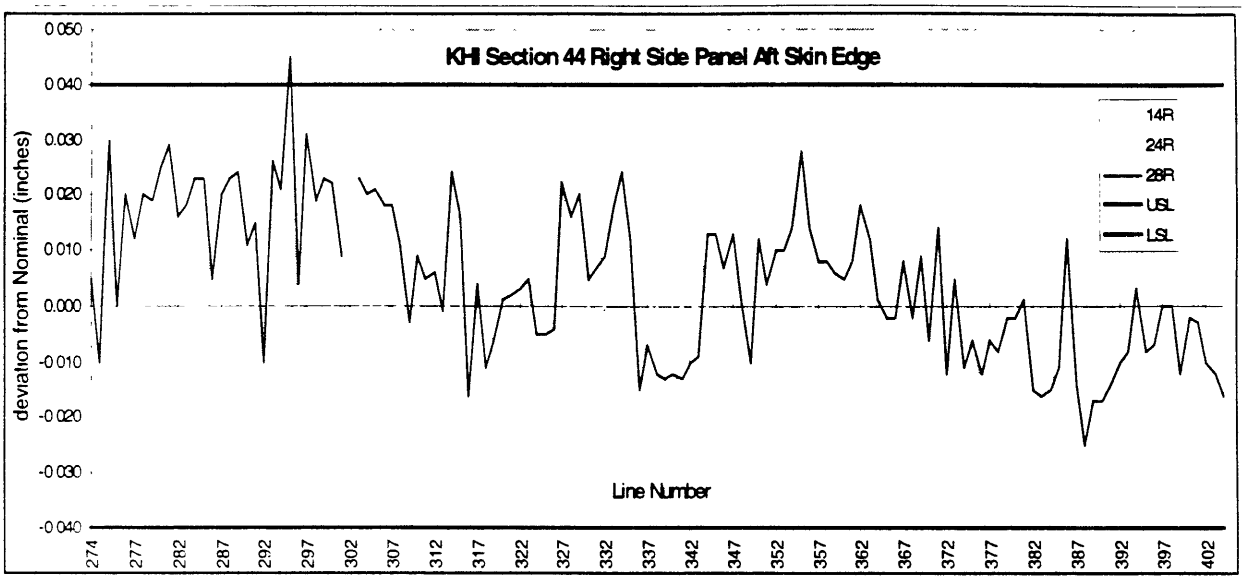

Figure 4.4 KHI KC measurements on section 44 right side panel aft skin edge

Statistics based on the vendor KC data are shown in Table 4.1. Process capability calculations show that KHI can meet engineering requirements most of the time, particularly in the case of a centered and stable process such as the left side panel. Cp values less than unity in the case of crown and right side panels are due to the trends noted above. Cp for the sample group of airplanes taken either before or after the process shifts are greater than unity. This is shown in Table 4.2.

KHI data for all 777s Manufactured through December 1997										
	Left Side Panel			Crown Panel				Right Side Panel		
Stringer	28L	24L	14L	14L	1L	1R	14R	14R	24R	28R
Mean	0.005	-0.003	0.006	-0.001	0.014	0.010	0.002	-0.010	-0.007	0.005
Std Dev	0.008	0.010	0.008	0.014	0.012	0.014	0.011	0.015	0.017	0.014
Cp	1.725	1.352	1.590	0.968	1.104	0.962	1.193	0.917	0.799	0.978
Cpk	1.522	1.266	1.351	0.933	0.727	0.720	1.120	0.692	0.660	0.859

Table 4.1 Section 44 aft skin edge KHI KC data for all 777s through December 1997

KHI data for 777s Manufactured from December 1996 through December 1997										
	Left Side Panel			Crown Panel				Right Side Panel		
Stringer	28L	24L	14L	14L	1L	1R	14R	14R	24R	28R
Mean	0.004	-0.002	0.005	0.007	0.021	0.018	0.002	-0.020	-0.018	-0.001
Std Dev	0.006	0.011	0.009	0.012	0.011	0.013	0.011	0.009	0.011	0.011
Cp	2.066	1.180	1.451	1.107	1.253	1.053	1.243	1.512	1.216	1.210
Cpk	1.855	1.131	1.272	0.926	0.599	0.585	1.174	0.767	0.665	1.178

Table 4.2 Section 44 aft skin edge KHI KC data from July 1996 through December 1997

Data from the block of airplanes in Table 4.2 result in the following observations:

- Cp values show that KHI has good control over the magnitude of random variations.
- Cpk values less than the corresponding Cp's indicate off-center processes.
- Cpk values less than both Cp and less than unity indicate that the combination of random variation and bias of the mean may represent a problem which can be improved by better process centering. Nevertheless, the parts appear to be within tolerance since almost all of the measurements fall within the upper and lower specification limits.

4.3.3.2 Analysis of vendor data based on part to part relationship

The part to part relationship between crown and side panels can be evaluated by subtracting the side panel KC from that of the crown (both measured at stringer 14). A plot of such derived data is shown in Figure 4.5. Given the common datuming and indexing scheme called out by UMED 40. the part to part relationship below should translate to the next build position and therefore be representative of what the downstream customers observe. A comparison (between CC335 and FBJ QA data) is performed in Section 4.4.

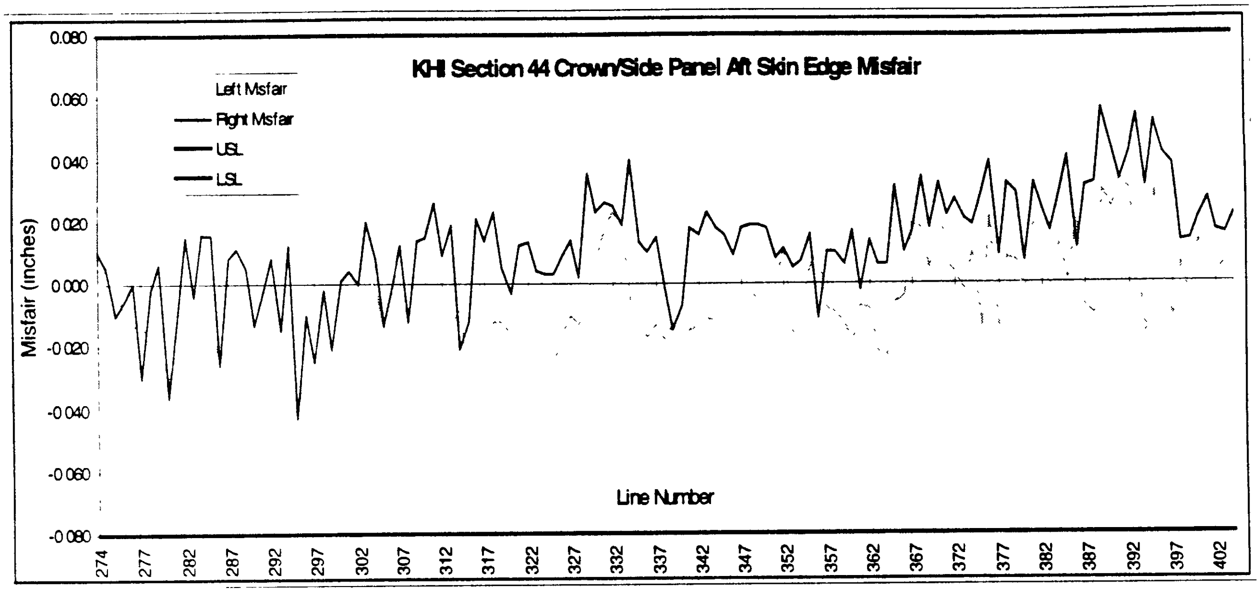

Figure 4.5 Section 44 crown to side panel length mismatch based on KHI KC data

The upper and lower specification limits in Figure 4.5 are based on summation of the individual panel tolerances (i.e. 0.040 + 0.040 = 0.080) although no explicit tolerance for lap misfair is called out on an engineering drawing. It is clear from Figure 4.5 that the vendor data do not explain the misfairs reported by FBJ. The following additional observations are made:

- A process shift to larger misfairs begins at around L/N 364, particularly for the right side panel. This point corresponds to the break in data flow from KHI that was discussed in Section 4.3.3.
- The largest mismatches in panel length occur between L/N 385 and L/N 395 but all of the airplanes are within tolerance.

4.3.3.3 Preliminary conclusions based on vendor data

Analysis of vendor data shows good variability control indicated by high Cp values but more attention should be paid to process centering and trend analysis. Data extraction and analysis is difficult because of slow information flow and the spreadsheet manipulations required. In some instances the points appear to lack randomness. This is indicated by long stretches of airplanes with points on the same side of the mean, points trending in a direction, and the fact that only one point is out of tolerance although the Cp's and Cpk's would predict more for the given number of sample points.

If the vendor data are accurate, the problems in final body join are introduced elsewhere in the process. To summarize the findings of the vendor data study:

- There differences between the convention used by KHI and Boeing to report KC data
- Confusion exists in Everett as to the meaning of KHI data
- KHI is chronically delinquent in providing KC data
- Format of data spread sheet is not conducive to statistical analysis because extensive sorting and conversion from airplane effectivity to line numbers must be performed first.

4.3.4 CC335 KC data

UMED 40 calls for HVC data to be taken at the aft skin edge before and after panel integration in order to monitor for elongation during assembly. The author compared before and after data during the internship and found them to be largely uncorrelated and not a reliable indicator of whether or not the panels were being elongated during fastening. There are several reasons why this is so:

1. Panels are indexed and set on second shift and the "before" set of HVC data are taken. The next day first shift inspects frame and floor beam alignment and if they can correct non-conformance reject mismatch conditions with a slight (+/-0.030) panel station shift they do so. This practice is referred to as "best fitting". Assembly procedures continue and prior to the next line move the "after" set of HVC data are taken. Thus before and after data are often taken with the panels deliberately shifted to different positions to accommodate the conflicting incentives of mechanics on different shifts. The incentives are in conflict because the assembly is over-constrained and each shift is responsible for satisfying a set of requirements that is mutually exclusive from that of the other shift (i.e. the second shift in CC335 indexes body panels to the features on the FAJ and first shift indexes to match floor beams and frames, see Section 3.1.5)
2. Panels move forward and aft during assembly without direct operator action due to mechanical vibration. The shims at the forward station (0.125 inches nominal) used to index the panels are typically removed after the panels have been indexed so there is no hard stop at either the forward or aft end.

3. Since the front end of the panel is not blocked during assembly elongation in the forward direction could occur and would not be measured by HVC because data is only taken at the aft end.
4. Measurement error is not considered. Based on feeler gage data obtained by the author during the internship measurement probably accounts for +/- 0.010.
5. Thermal expansion and contraction are not accounted for (Section 4.3.2). In a given 24 hour period the author observed maximum temperature changes in the factory of about 2°F which would account for about 0.010 inches of change in panel length (assuming that the panel temperature changed by the same amount as ambient air temperature).

Comparison of before and after HVC data give meaningless results because changes in the KC values are due to many other factors besides panel elongation and it is not possible to know which ones affected a given airplane. The "after" data set correlate with final body join QA inspection records whereas the "before" set do not (Section 4.4). Consequently, of the two conflicting data sets, post integration is more reliable and pre integration HVC data are not considered in this thesis. During the internship the author suggested that CC335 be allowed to discontinue the "before" HVC measurements but this was not done. At the end of the internship the shop was still collecting the non-value added pre-integration data.

Section 5.1.5 presents a qualitative discussion of the effect of panel integration on length based on the author's measurements during the internship. Most Boeing personnel believe that the effect is very small and the author concurs.

CC335 HVC data are with respect to nominal at zero and negative numbers indicate that the panel is short of nominal by that amount and versa visa for positive numbers. As was the case with the KHI spreadsheets, Everett KC data require sorting, conversion from effectivity to line number, and formatting in order to perform statistical analyses. The following sections present the results of these efforts. Line numbers are disguised.

4.3.4.1 Analysis of CC335 part to tool KC data

Figure 4.6 shows a summary of CC335 data for the aft skin edge of section 44 body panels after fastening. A mechanic collects the data in accordance with an O&IR job (operating and inspection requirement) that specifies which KCs to measure. A mitotoyo depth gage is inserted through features secured to the aft end gate and offset by 0.125 inches at the stringer locations shown in Figure 3.4. The spread of the data is much larger than that of the vendor. The upper and lower specification limits are set at +/- 0.030 (as opposed to +/- 0.040 for the vendor data) and few points fall within tolerance. A marked positive bias is evident indicting that the panels are either set too far back at the forward edge from which they are indexed or the panels are too long (assuming that measurement error is only about +/- 0.010), or some combination of the two effects. Per UMED 40 (Section 4.3.1) "measurements are not made at the front of the section due to primary index points". Consequently, it is not possible to determine what causes the offset by simply examining the data.

The following additional observations concerning the CC335 shop data are made:

- Many data points are missing.
- In order to include all the data the vertical axis must span a large range which makes detailed analysis difficult.
- Many points on a given airplane are identical indicating that the data are suspect.

After L/N 364 the data are unreliable. From about L/N 373 through 392 each point on a given airplane is co-linear with the other measurements on the same airplane and there is a large negative offset. If these data were accurate at least two significant effects would be directly observable in production:

1. The aft skin edge of the crown and side panels would be flush.
2. The skin gaps in final body join would either be very wide (by about 0.250 for the airplanes which are reported to measure -0.300 short of nominal) or the section 44 body panels would touch the section 46 body panels (for the airplanes which are reported to measure 0.300 long

of nominal). In both instances considerable attention would be drawn because of the magnitude of deviation from the already poor historical performance.

Since the data are in conflict with direct observations made during the internship, it is concluded that data after L/N 364 are corrupt.

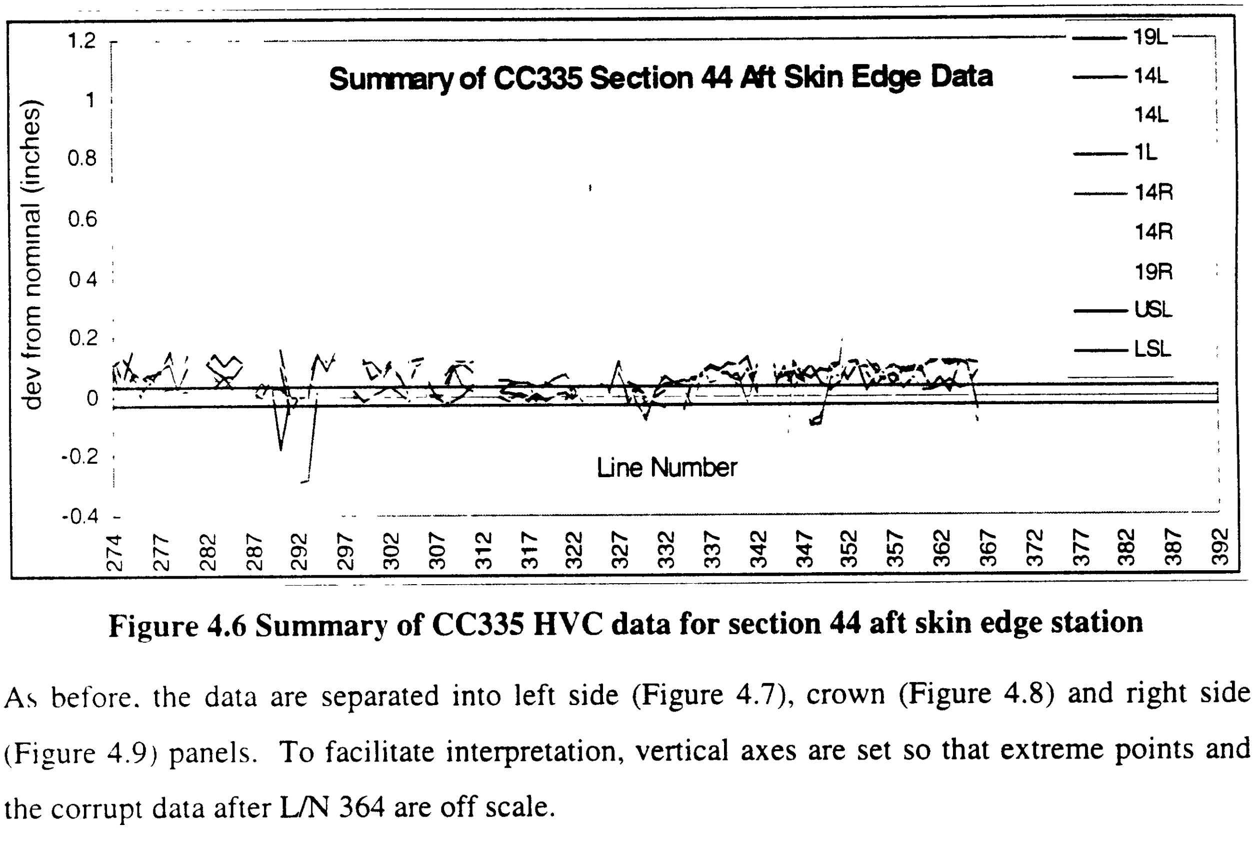

Figure 4.6 Summary of CC335 HVC data for section 44 aft skin edge station

As before, the data are separated into left side (Figure 4.7), crown (Figure 4.8) and right side (Figure 4.9) panels. To facilitate interpretation, vertical axes are set so that extreme points and the corrupt data after L/N 364 are off scale.

One can conclude from the specification limits and general appearance of the plots that CC335 records more variability than does the vendor and that CC335 has tremendous difficulty meeting specification limits. The following additional observations are made:

- There is a positive bias on all three body panels.
- The large variability may mask underlying cyclicality.
- Vendor and CC335 data differ significantly in terms of range, dispersion, and trends.

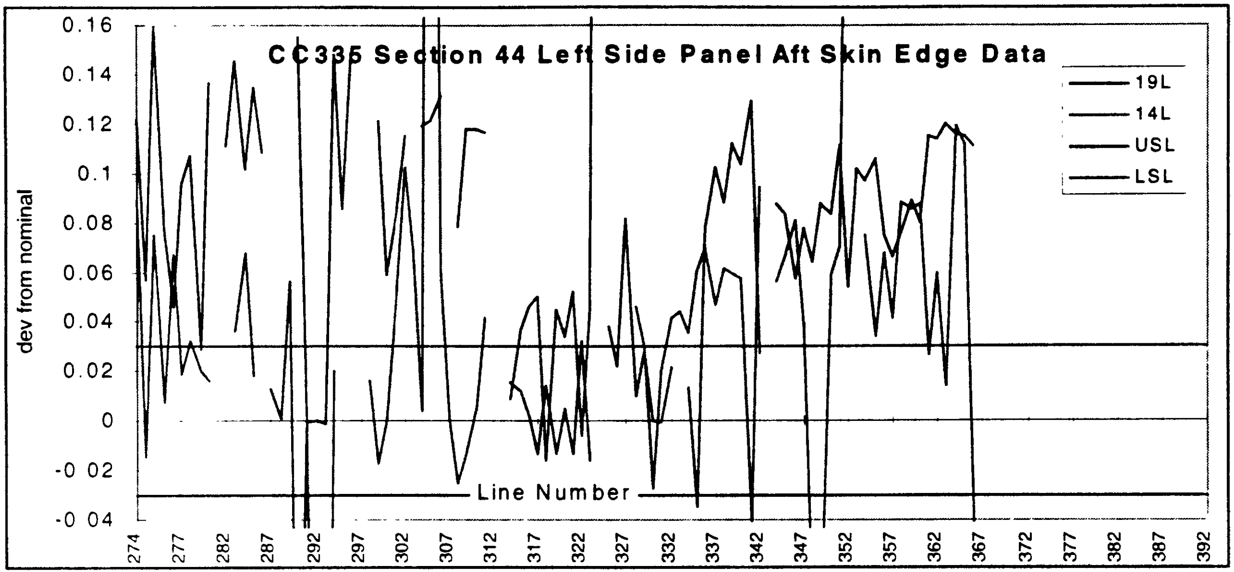

Figure 4.7 CC335 HVC data for section 44 Left Side Panel aft skin edge station

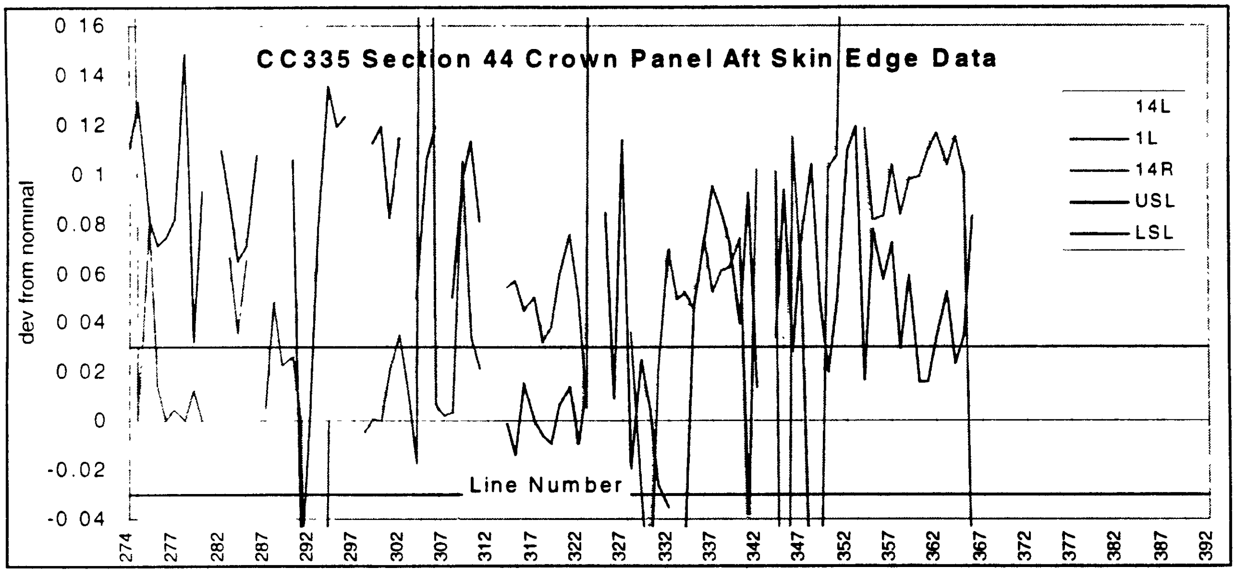

Figure 4.8 CC335 HVC data for section 44 Crown Panel aft skin edge station

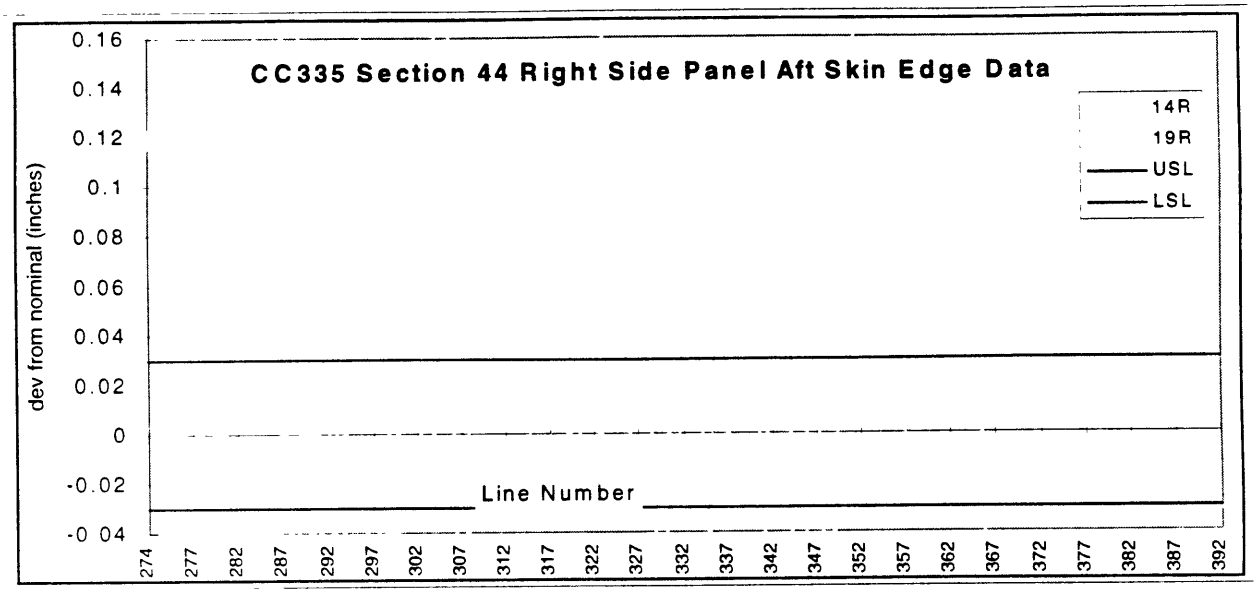

Figure 4.9 CC335 HVC data for section 44 Right Side Panel aft skin edge station

Statistics based on CC335 data are shown in Table 4.3 and Table 4.4. Values for Cpk are undefined because all of the process means are outside of the specification limits. Trends in the vendor data are either masked by noise or absent. Comparison of Table 4.3 with Table 4.4 shows an insignificant difference between data sample sets (i.e. the process is consistently out of control since the start of the program).

CC335 KC data for all 777s Manufactured through June 1997							
	Left Side Panel		Crown Panel			Right Side Panel	
Stringer	19L	14L	14L	1L	14R	14R	19R
Mean	0.076	0.044	0.066	0.059	0.060	0.061	0.077
Std Dev	0.050	0.124	0.122	0.048	0.158	0.193	0.051
Cp	0.202	0.081	0.082	0.207	0.063	0.052	0.195
Cpk	Undefined	Undefined	Undefined	Undefined	Undefined	Undefined	Undefined

Table 4.3 Section 44 aft skin edge statistics based on CC335 KC data for all 777s manufactured through June 1997

CC335 KC data for 777s Manufactured June 1996 through June 1997							
	Left Side Panel		Crown Panel			Right Side Panel	
Stringer	19L	14L	14L	1L	14R	14R	19R
Mean	0.073	0.066	0.086	0.047	0.070	0.052	0.068
Std Dev	0.040	0.118	0.126	0.041	0.141	0.135	0.044
Cp	0.248	0.085	0.079	0.243	0.071	0.074	0.229
Cpk	Undefined	Undefined	Undefined	Undefined	Undefined	Undefined	Undefined

Table 4.4 Section 44 aft skin edge statistics based on CC335 KC data for 43 777s manufactured from June 1996 through June 1997

Data from the block of airplanes in Table 4.4 result in the following observations:

- The process mean is outside the upper specification limit (0.030) in every case.
- Cp values significantly less than unity indicate that random variation is also a problem.

4.3.4.2 Analysis of CC335 data based on part to part relationship

The part to part relationship between crown and side panels can be analyzed by subtracting the side panel KC from that of the crown (both measured at stringer 14) as was done in Section 4.3.3.2. This is shown in Figure 4.10. Note that these data represent the condition of the section after fastening and therefore should be representative of what final body join observes. Disagreement between KHI and CC335 part to part data can be explained on the basis of measurement errors, suspect data, violation of indexing schemes, or some combination. After panel integration in CC335, however, relative movement between crown and sides is infeasible and conflicts between data sets in CC335 and final body join must be due to either measurement error or suspect data.

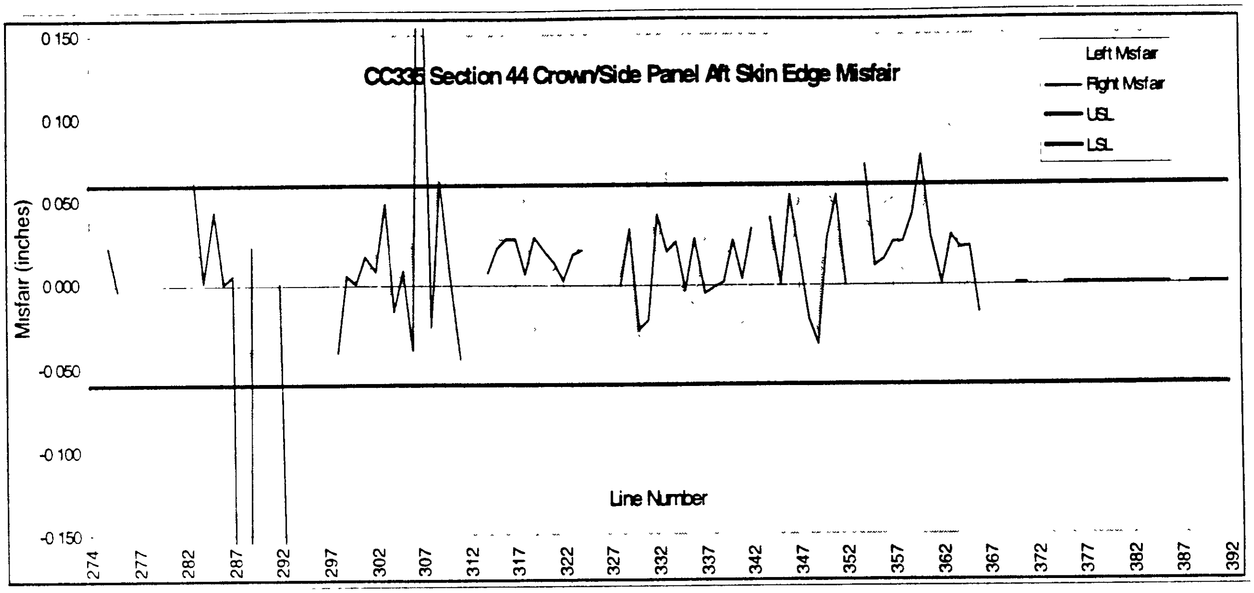

Figure 4.10 Section 44 crown to side panel length mismatch based on CC335 KC data

The upper and lower specification limits in Figure 4.10 are based on summation of CC335 build plan tolerances (i.e. 0.030 + 0.030 = 0.060) although no explicit tolerance for lap misfair is given on an engineering drawing. As much as CC335 has trouble meeting specification limits for individual panel positioning, they have difficulty with the part to part relationship. This is particularly problematic because the part to part fit is on the outer skin and readily observable to internal and external customers. CC335 data shows a trend after about L/N 343 toward larger misfairs which coincides with a vendor shift in the crown and right side panels (Section 4.3.3.1). Unfortunately, because CC335 data after L/N 364 are corrupt, further comparisons are not possible. The following additional observations are made:

- Points equal to zero are questionable because this implies that the crown and side panels are perfectly flush. A more likely explanation is that a single data point was inputted repeatedly.
- The largest mismatches in panel length occur after L/N 350. This coincides with the start of the internship and helps explain why Final Body Join was eager to have the issue looked into: it was an immediate problem that had apparently been worsening over time. It may also explain why the problem was "tolerated" for four years. Only when it got bad enough to threaten the delivery schedule did it receive attention. The theme seemed to recur throughout the factory: work around a problem until it is a crisis and it's not a crisis unless it threatens production.

4.3.4.3 Preliminary conclusions based on CC335 data

In a properly designed and functioning hardware variability control (HVC) system the KC data should lead one to the source of the problem. In this case one would conclude that:

- When KHI measures the body panels they are in tolerance.
- When CC335 measures the aft skin edge of completed body sections the panels are too far aft.
- CC335 data match the problem described by final body join.
- The information necessary to identify the problem was available to CC335 for four years but no one reacted to it until it threatened production (the factory was ramping up production at around L/N 350 from an airplane every four days to one every three days).
- Since the parts are in tolerance at KHI and out of tolerance after leaving CC335 the panels must either be elongating during shipment and/or assembly or CC335 is mis-indexing them too far aft. Elongation of panels during integration in CC335 is discussed in Section 5.1.5.

4.4 Comparison between KHI and CC335 data

In this section a comparison between the KHI and CC335 data is made to check for internal consistency. KHI and CC335 data should differ by only the random variation inherent within the respective measurement processes (taking for granted Boeing's assumption that temperature effects are negligible). That this is not the case is shown in Figure 4.11 and Figure 4.12. To repeat a now familiar theme, the differences could be due to measurement error or violation of indexing plans, or a combination of the two.

Final Body Join began recording the misfair at whichever side was worst on L/N 350. These data are recorded manually during third shift when the body sections are joined. Note that the correlation between KHI and CC335 is poor but that the correlation between CC335 and FBJ is fairly good.

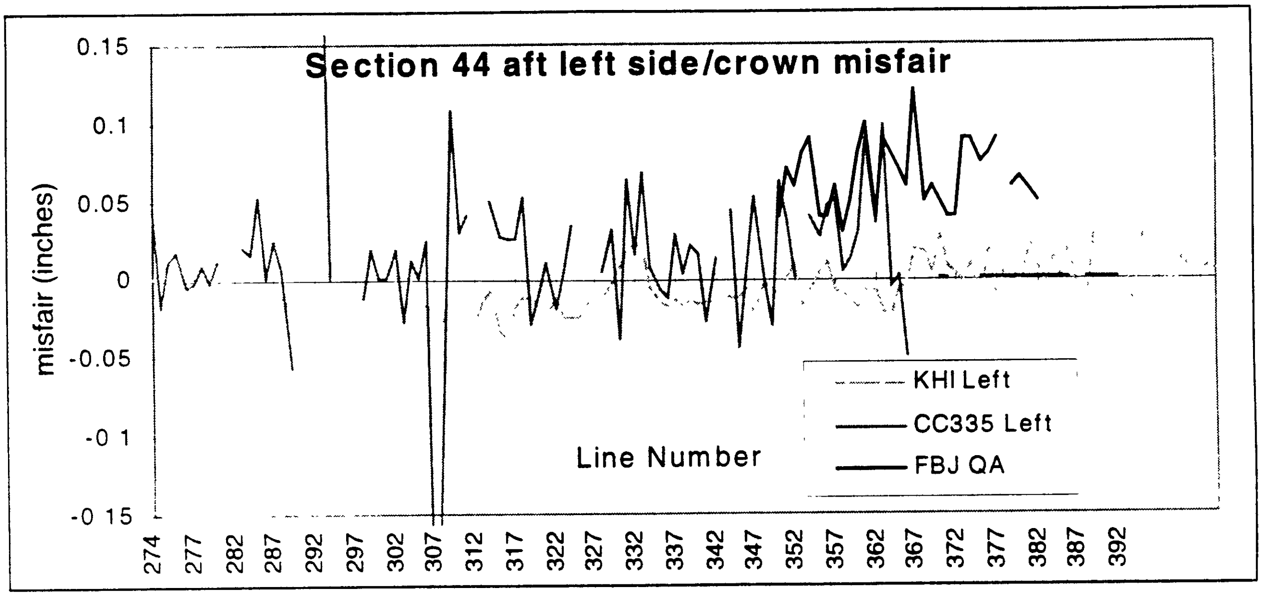

Figure 4.11 Left side/crown misfair based on KHI, CC335, and FBJ QA data

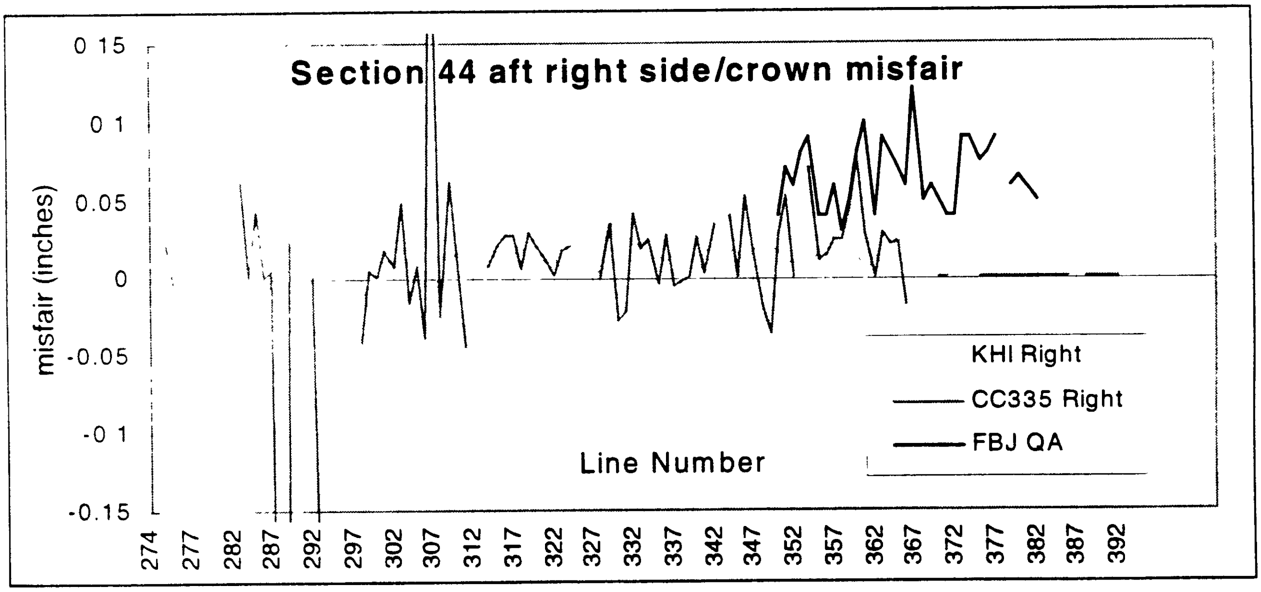

Figure 4.12 Right side/crown misfair based on KHI, CC335, and FBJ QA data

Another test of fit between KHI and CC335 includes a scatter plot of one versus the other. Figure 4.13 and Figure 4.14 show CC335 left and right crown/side misfair, respectively, versus the corresponding KHI values (values obtained from Figure 4.5 and Figure 4.10). There is much more spread along the CC335 axis (*x*) than along KHI's (*y*) and the data do not associate in a linear fashion as would be expected. For comparison Figure 4.15 shows CC335 data versus FBJ QA data from L/N 350 through L/N 364. The correlation is good.

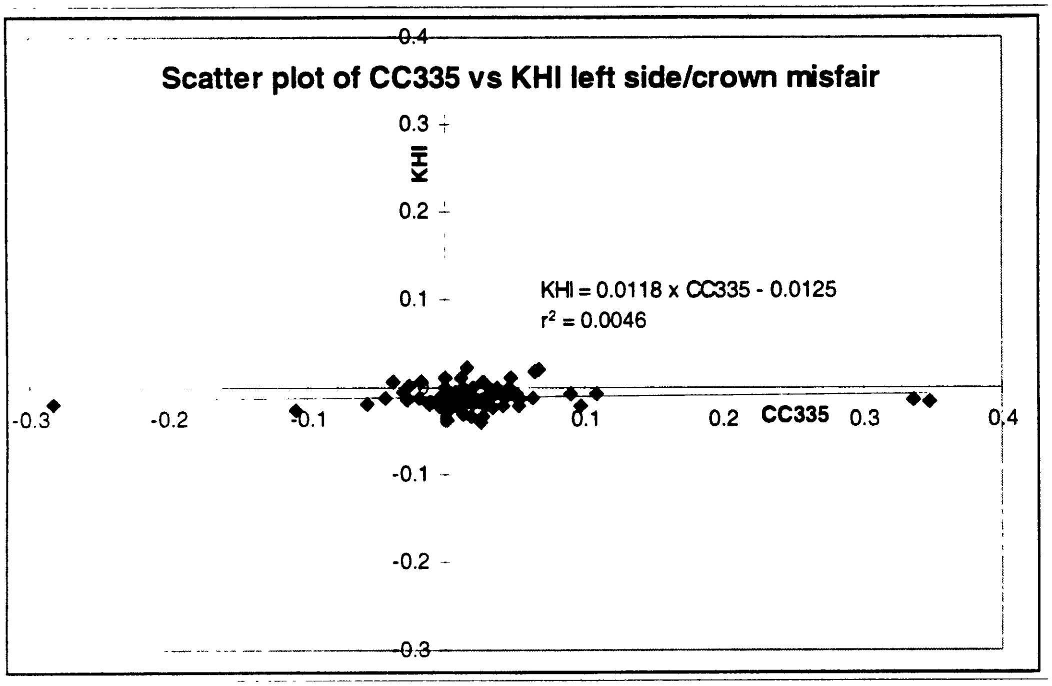

Figure 4.13 Scatter plot of CC335 vs KHI left side/crown misfair

The value r^2 shown in Figures 4.13 through 4.15 is the correlation coefficient squared which approximates the fraction of the total variation in the data that is accounted for by a relationship between the plotted variables. The square root of this value (i.e. r) can be used to evaluate the significance of the relationship between the variables. In Figures 4.13 and 4.14 there are 92 data pairs resulting in $\nu = 92-2 = 90$ degrees of freedom. In this case an r value of 0.1726 is needed to give 90% confidence of a correlation between KHI and CC335 data. Referring to Figure 4.13 (which has a higher correlation than Figure 4.14), since $(0.0046)^{1/2}$ is only 0.068 which is less than 0.1726 we conclude that the data do not correlate. In Figure 4.15, on the other hand, 11 points are plotted with 9 degrees of freedom. $r = (0.8812)^{1/2} = 0.939$ which is much greater than the 0.7348 needed for 99% confidence that there is a correlation.

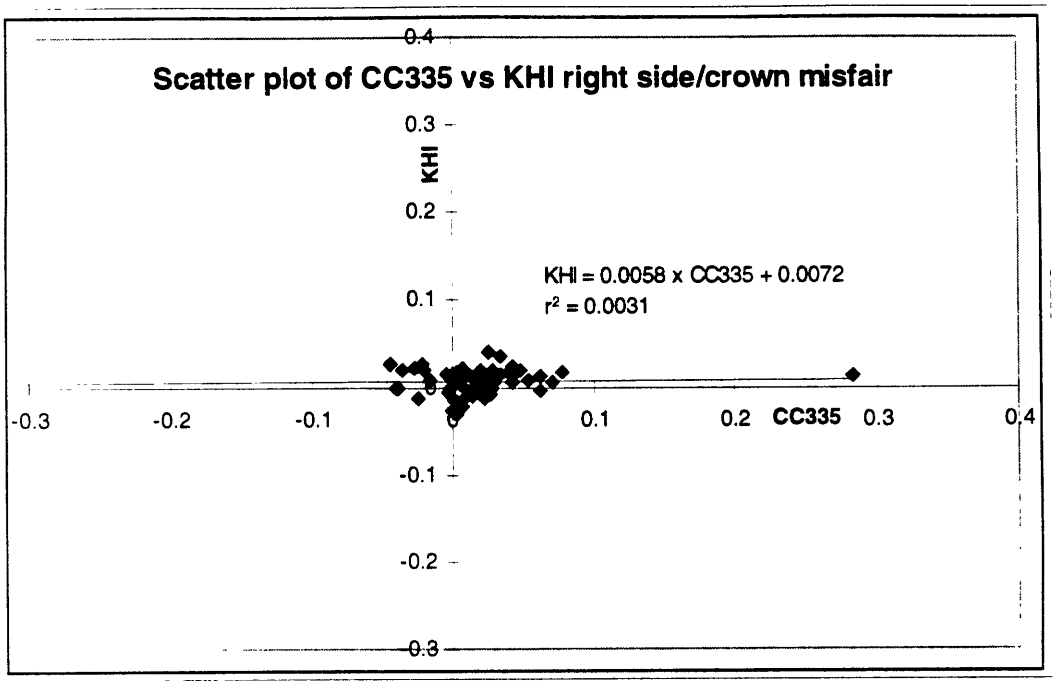

Figure 4.14 Scatter plot of CC335 vs KHI right side/crown misfair

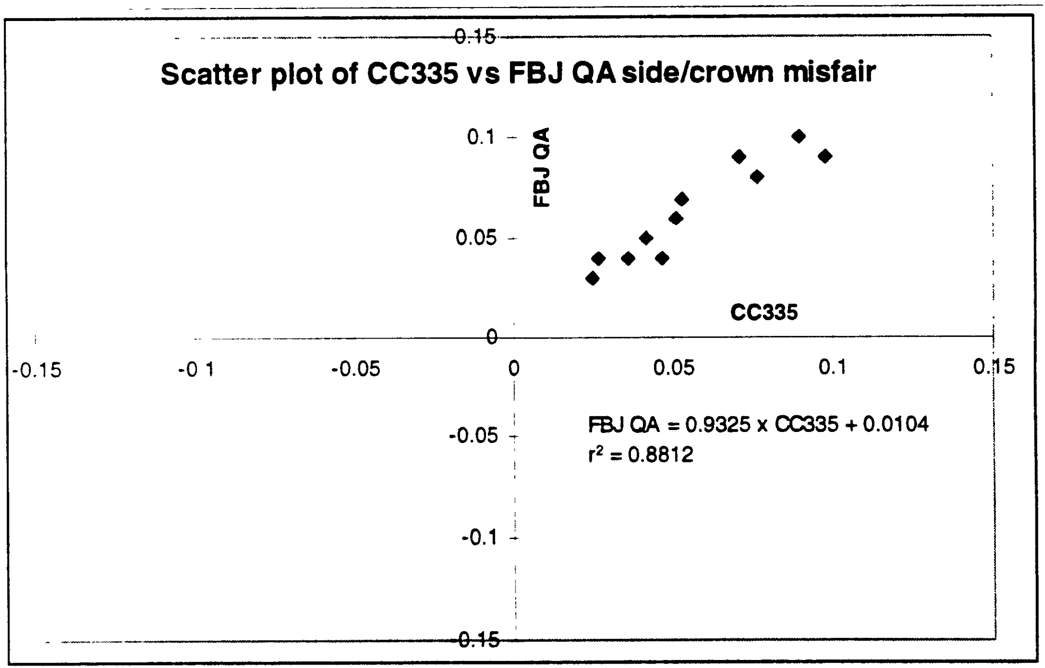

Figure 4.15 Scatter plot of CC335 vs FBJ QA side/crown misfair

4.5 Summary of Chapter

KHI and Boeing HVC data are inconsistent. KHI data seem to indicate that there is not a problem at the vendor level and that the section 44 aft skin edge station trimming process is centered and capable. The KHI data are almost "too good" because for the calculated values of Cp and Cpk one would expect more than one point out of 1,310 to be outside of the tolerance limits. CC335 data, on the other hand, indicate that the process is off-center and incapable of meeting tolerances. The CC335 data match the observations made by final body join over a relatively short span of airplanes.

At face value these results lead one to believe that CC335 introduces the variation by violating the index plan. Confounding the matter, however, is the fact that KHI and CC335 part-to-part data do not correlate as they should because of the common indexing scheme. This inconsistency makes it difficult to determine the real source of the problem because both data sets cannot be correct. Not even temperature effects would cause the crown panel to grow relative to the side panels. When the panels are placed side by side during assembly in Everett the crown panels are visibly longer than the side panels although the KHI KC data suggest that they should be of equal length.

Temperature may be a source of variation in overall panel length that is not adequately accounted for in Boeing's manufacturing processes.

Measurement error is not quantified in any of the formal HVC KC processes examined. The author estimates that it is approximately +/-0.010 for the data presented in this chapter.

Panel elongation during integration in CC335 may explain the conflict between KHI and CC335 data sets, however, this will be ruled out later in Section 5.1.5.

The problem existed for a long time before receiving attention. This may be due to more pressing issues competing for the attention of limited resources. It may also be because the heavy emphasis on schedule adherence forces shops to work around problems as much as possible in order to make rate. Because of this, efforts are directed toward creating symptomatic solutions to problems as though they were isolated events. This weakens the ability of the organization to reach solutions at a fundamental level thereby fostering an even greater dependence on reactive problem solving.

5. Chapter 5 - Diagnosis of problem using local measurements

The KC data in Chapter 4 indicate that CC335 introduces out of tolerance variation by compromising the indexing of section 44 body panels. UMED 40 (Section 4.3.1) specifies that excess skin at the aft end must be trimmed in CC335. Such a requirement would give CC335 incentive to properly index the panels (so that they wouldn't have the work of trimming) and also to aggressively communicate problems back to the vendor. Unfortunately for final body join the UMED 40 guidance to measure and trim the section 44 aft skin edge is not reflected on the engineering drawings that dictate the build process.

The build plan, an engineering drawing that is different from UMED 40, assumes that panels arrive at net trim and are indexed from the forward edge so that CC335 has no control over the aft skin edge station. Therefore, even though length variation is washed to the aft skin edge, CC335 is not required to measure the station location, much less trim it to nominal. HVC measurements are called out, but these are not utilized in the shop. HVC data, when taken, are uploaded to a central database and mechanics in the shop rarely received feedback. HVC jobs are perceived as little more than a non-value added nuisance that interfere with the task of building airplanes. Given this state of affairs, it is remarkable that CC335 HVC data correlate with final body join QA records at all (see Figure 4.15). Recall from Section 4.3.3.1 that the shop data became corrupt at about L/N 364 at which point the correlation between CC335 and final body join QA data sets ended.

Based on the "official KC data", a possible solution would be to incorporate the UMED 40 skin edge measurement and trimming requirements into the directive engineering drawing. CC335 would be forced to correct the problem that the KC data indicate is caused by their practice of "best fitting". The problem with this approach, however, is that the aft end crown to side panel misfair is not accompanied by a corresponding misfair at the forward end. This means that the crown panels are longer than the sides and that CC335 would be required to correct a condition that they are not fully responsible for causing (although forcing them to do so would provide incentive for them to communicate the condition to their supplier instead of passing it to their customer).

5.1 Informal measurements

In this section the author examines various independent measurement and data sources that are not part of the formal HVC program. Efforts were made to repeat measurements on fixed hardware features in order to estimate the magnitude of measurement error. Conflicts between information sources were sought to reduce the risk of confirmation bias (wherein a researcher recognizes only data that confirm his or her hypothesis and ignores conflicting data). The author concedes that this goal was not completely realized and section 5.1.3.1 describes an instance where a statistically significant signal should have been recognized but was left unresolved until after the internship ended.

5.1.1 Difference in length between crown and side panels

A first step in the investigation involved checking the part to part length relationship between the crown and side panels. If the panels were the same length at stringers 14L and 14R as the KHI data indicated, misfair at the aft station must also be observable at the forward station. An easy way to spot check whether or not KHI's data are believable is to measure the amount by which the crown panel protrudes aft from the side panels at station 1434 and comparing this to the condition at the forward end (station 1035).

At the start of the informal investigation L/N 364 was in FBJ and KHI had supplied Boeing with aft skin edge KC data up to L/N 363. Three airplanes earlier (the June 1997 rework incident described in Section 3.2.1) the aft skin edge of the section 44 crown was trimmed in FBJ due to excess length which caused insufficient gap between the section 44 and section 46 crown panels. In fact, of the previous sixteen airplanes, fourteen had a condition where the crown panel protruded aft of the side panels with the average protrusion being 0.06 inches and no corresponding offset at the forward end. KHI data for all of these airplanes, however, indicated that the panels were of equal length within 0.010 inches. A work procedure known as "greenline[16]" was initiated by final body join requesting that a check be performed on the airplanes between FBJ and CC335 and that any misfairs greater than 0.030 be trimmed prior to arrival in CC131. The greenline was dispositioned such that FBJ would be required to perform the rework.

Instead of receiving support to prevent the problem from reaching final body join, final body join was given the added work of correcting the condition when and if it occurred again. FBJ thus had a strong incentive to best fit around the problem in order to make rate. They cancelled the green line which they had hoped would precipitate a root cause analysis and dropped the tail of subsequent airplanes that had the problem condition (see Section 5.2.3 for laser alignment data). The resulting lack of further reject tag activity back to the section 44 build shop supported CC335's contention that there was no problem. Each entity in the supply chain thus has the incentive to best fit around the problem and pass it to their customer.

With a feeler gage that had a smallest division of 0.005 the author checked for misfair at stringers 14L and 14R at the section 44 forward and aft end crown to side laps. These measurement data were used to prepare the overhead view as shown in Figure 5.1. L/N 373 and 374 are shown as they were measured during the assembly process. The numbers in the diagrams are in thousandths of inches and are the averages from all of the post-fastening measurements taken (steel tape data is also shown on the figure and is discussed in Section 5.1.2). Negative numbers indicate the crown skin edge is aft relative to the adjacent side panel.

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[16] Appendix 6 contains a glossary of Boeing specific terms, acronyms, and definitions that are used throughout the thesis.

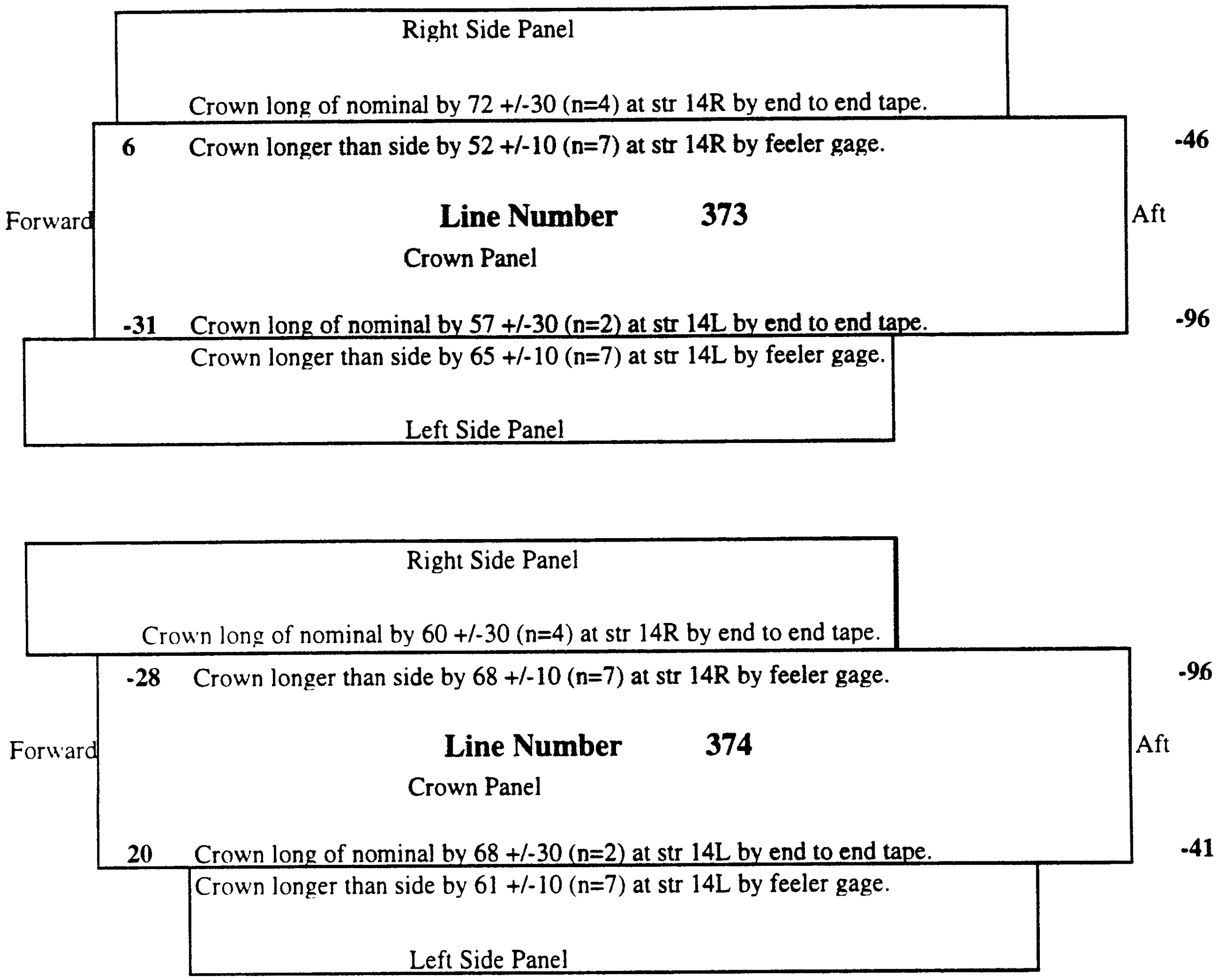


Figure 5.1 Overhead view of misfair and steel tape measurements on two airplanes

The difference of the aft measurement from the forward measurement is the length mismatch between the crown and adjacent side at stringer 14. For example, Figure 5.1 shows that on L/N 373 the crown is 6-(-46) = 52 thousands of an inch longer than the side at 14R and -31-(-96) = 65 thousandths longer than the side at 14L. Measurements from L/N 364 through L/N 403 are plotted in Figure 5.2.

Misfair at the forward end of section 44 is not sufficient to explain the aft misfair. In general CC335 maintains the forward end misfairs to less than 0.030 inches and after the final body join incident that occurred in September of 1997 paid particular attention to indexing. CC335 indexing contributes, but is not the sole cause of the problem. Also, in CC335's defense, the index points for the crown panels are at stringer 12L and 12R and at 19L and 19R for the sides.

Thus, misfair at 14L and 14R could be explained even with perfect indexing if the skin edges were not straight but instead had a slight curve. This situation was observed several times during the course of the investigation where crown and sides were indexed exactly at nominal and misfairs on the order of 0.020 were observed at the laps.

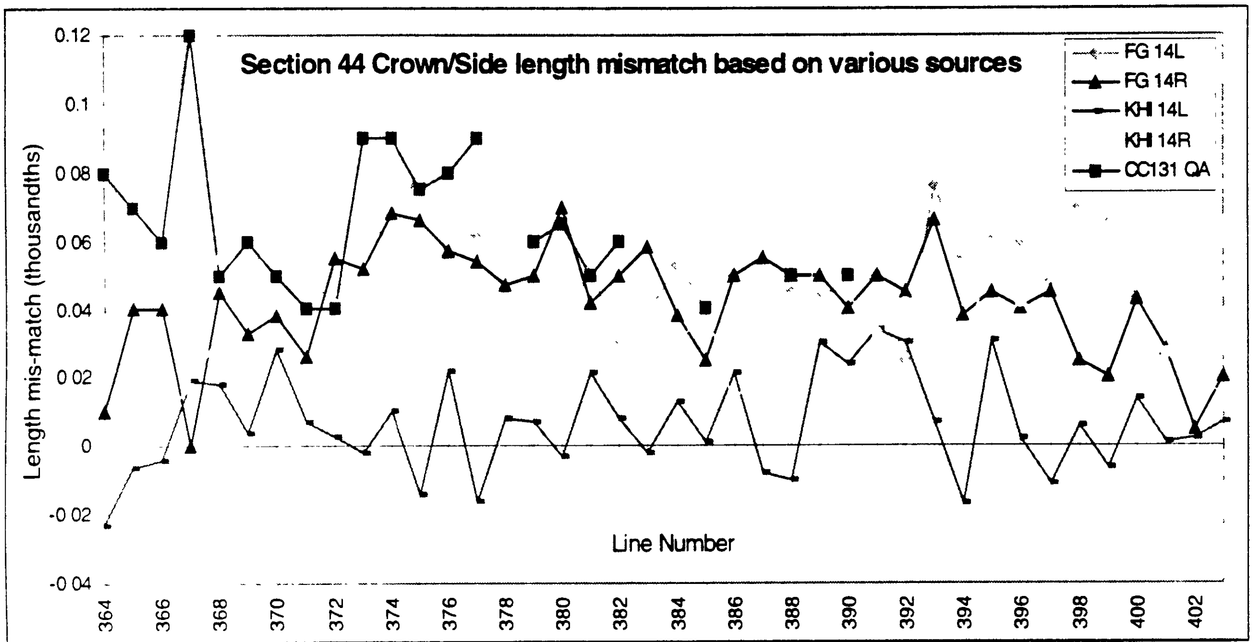


Figure 5.2 Section 44 Crown Panel length in excess of Side Panel at stringer 14L and 14R

Seven sets of measurements were taken on the first fifteen airplanes in Figure 5.2 in order to estimate measurement error. Each measurement was the average of two individual measurements taken at the same time. The airplanes were followed through the assembly process (some movement was noted on measurements from before and after fastening but the excess length did not change due to riveting) and standard deviations on the order of 5 thousandths were calculated. Thus the feeler gage (FG) data are considered accurate to +/- 0.010 inches. Figure 5.2 also shows KHI KC and final body join QA data. The feeler gage measurements track closely with the QA data but not with that of KHI. Note, however, that after about L/N 388 KHI data at 14R begins to match the part to part feeler gage measurement (the two blue lines in Figure 5.2 converge) but that 14L agreement is still poor (the two green lines do not converge).

The author contends that KHI began troubleshooting their KC measurement process around L/N 364 when they learned of the problem in Everett. They then delayed reporting of KC data for several months (recall that there was correlation between CC335 KC data and FBJ QA up to L/N 363 but no correlation with KHI). After L/N 363 CC335 data are corrupt. This precludes correlation between CC335 and KHI data but local measurements with feeler gage provide some measure of crossover. KHI data did not track with Everett data at all until L/N 363; began to track slightly after L/N 364; and then tracked closely after L/N 388.

The correlation coefficients between Everett and KHI data are summarized in Table 5.1. The unexplained shift from no correlation between Everett and KHI to statistically significant correlation after L/N 116 leads the author to believe that KHI identified and corrected problems with their KC measurement on crown and/or side panels sometime around L/N 389 but did not notifiy Everett of the change.

Sample Group	**Correlation Coefficient**	**Significance**
CC335 vs. KHI @14L, up to L/N 363	0.067	None
CC335 vs. KHI @14R, up to L/N 363	0.056	None
CC335 vs. FBJ QA	0.939	>99%
Feeler gage vs. KHI @14L, L/N 364-388	0.048	None
Feeler gage vs. KHI @14R, L/N 364-388	0.085	None
Feeler gage vs. KHI @14L, L/N 389-406	0.284	<90%
Feeler gage vs. KHI @14R, L/N 389-406	0.807	>99%

Table 5.1 Correlation between various data sets for section 44 aft skin edge misfair

5.1.2 Steel tape measurements

Forward to aft end measurements of section 44 crown panels at stringers 14R and 14L were made with a calibrated steel tape. The tape had a smallest division of 1/8 inch (0.125) and the nominal panel length per drawing is 398.830. Measurements were performed by the author and a process engineer. The measurement results are given in Table 5.2. Each number represents the average of four measurements with a standard deviation of about 15 thousandths inches. This suggests an accuracy of 30 to 45 thousandths which is constant with the following thumb rule: accuracy is about one third of the smallest division (40 thousandths in this case). Steel tape data in Table 5.2 indicate that the crowns are between 45 and 125 thousandths long of nominal.

Steel tape measurement data in CC335 inches over nominal (398.830) at 75F		
L/N	14L	14R
369	0.076	0.066
370	0.066	0.093
372	0.072	0.085
373	0.057	0.072
374	0.068	0.06
376	0.072	0.085
389	0.126	0.089
390	0.108	0.11
391	0.132	0.12
392	0.086	0.073
AVG	0.086	0.085

Table 5.2 Crown panel length in excess of nominal based on steel tape measure at Everett

In response to pressure and data from Everett, KHI measured panels in Japan with a steel tape. Initially they measured only L/N 393 and reported crown lengths of 398.940 inches and 398.880 at stringers 14L and 14R respectively. Interestingly, KHI cited a nominal of 398.915 which is 0.085 greater than engineering. The KHI representative, under the impression that the nominal value was in fact 398.915, demonstrated pride in the fact that the crown was within tolerance (+/- 40) at 25 thousandths over at 14L and 35 thousandths under at 14R. It was brought to his attention that the correct nominal value was 398.830 and it was requested that KHI confirm the value to which they had been trimming panel length.

Steel tape measurement data from KHI inches over nominal (398.830) at		
L/N	14L	14R
392	0.11	0.05
394	0.02	0.05
395	0.07	0.07
AVG	0.067	0.057

Table 5.3 Crown panel length in excess of nominal based on steel tape measure at KHI

KHI did not directly respond to this request but in subsequent communications listed the correct nominal value of 398.830. KHI reported the steel tape measurements shown in Figure 5.3 along with temperature data. They made the argument that thermal expansion and contraction would bring the panels to nominal when they equilibrated in Everett. KHI did not explain the system of temperature compensation in use although they were requested to do so. KHI also did not explain how they could seasonally adjust their trimming process for changing differences between KHI and Everett (i.e. KHI is warmer than Everett in the summer but colder in the winter so if KHI trims long in the summer they must also trim short in the winter. Upon further questioning KHI stated that the assembly FAJ was constructed of aluminum so that thermal expansion and contraction effects cancelled. Under hot conditions, it was explained, the FAJ expands with the panel and by resulting in a longer trim at the higher temperature so that when the panel contracts it will be at the nominal length. The opposite occurs in the cold. KHI did not state at which temperature the nominal length would occur. The author recommends that Boeing establish one.

The calculation for thermal contraction given the KHI data on L/N 392 is as follows:

Data	Equation
Thermal expansion coefficient of Al: $\alpha_L = 1.2 \times 10^{-5}$ in/in°F	$\Delta L = \alpha_L \times L \times \Delta T$

Temperature difference = 10°F

Panel length = 398.830 in

$\Delta L = 1.2 \times 10^{-5}$ in/in°F x 10°F x 398.830 in = 0.048 inches

KHI's argument is plausible. At 75°F all of the values in Table 5.3 should be about 0.050 less and therefore all except one will be within tolerance. When L/N 392 was measured in Everett, however, it was long. This leads to the following concerns with KHI's temperature argument:

- The steel tape has a thermal expansion coefficient about half (6×10^{-6} in/in°F) that of Al. Correcting for this effect would lead to a length contraction of only 25 thousandths from 85°F to 75°F vice the 50 thousandths predicted by KHI.

- Were the panels thermally equilibrated at 85°F when the measurements were taken? The smaller steel tape (with a much higher surface area to volume ratio than the body panel) would be expected to have a much higher thermal diffusivity and be more effected by fluctuations in temperature unless both tape and panels were maintained at the same temperature for some soak period. In all likelihood, if the daytime temperature was 85°F and the average temperature over the last several days was lower than this value, then the small tape would be warmer than the panel. Then the expected thermal contraction would be less than 25 thousandths when measured by steel tape at 75°F.

5.1.3 Floor assembly jig measurement features

An independent set of measurement data were obtained based on features of the FAJ. Measurement indexes located forward and aft at stringers 1, 12, and 19 (left and right) on each of the FAJs with nominal offset values of 0.125 were measured with a feeler gage having a smallest division of 0.005 inches. These measurements resulted in the exaggerated overhead views shown in Figure 5.3. The numbers on either end denote the measured offset in inches based on the average of between two and four individual measurements taken at the same time (std deviation = +/- 0.003). Measurement error is estimated to be approximately +/- 0.006 at either end of the FAJ or about +/-0.012 inches for overall panel length by this method. Measurements were taken over a period of several days before and after panel integration to evaluate elongation. The numbers at the crown to side lap indicate the misfair measurement discussed in earlier in Section 5.1.1 and are the same as those shown in Figure 5.1.

Figure 5.3 shows that on L/N 380 the right side panel was nominally indexed at 0.125 inches from the tool feature at the forward end of stringer 19R and that it did not move or elongate during fastening. The corresponding aft skin edge is 40 thousandths aft of nominal indicating that the panel is long of nominal by 0.040 at stringer 19. The crown panel appears mispositioned aft on the left side and slightly forward on the right and extends aft by over 0.100. The left side panel is positioned 0.025 forward of nominal and aft it extends about 0.030 aft of nominal indicating excess length of about 0.055. As mentioned earlier, CC335 interpreted the build plan to allow +/-0.030 of play on the forward index. Based on Figure 5.3 L/N 380 is not even in accordance with this "best fitting" criterion. L/N 381 is indexed within 0.005 inches of nominal before fastening but post integration measurements show that the left side panel shifted forward about 0.020 inches (perhaps before riveting to match floor beams or frames and avoid NCR activity or the panel may have shifted during fastening due to vibration).

The data shown in Figure 5.3 were collected beginning with L/N 377 and continued after the internship ended. These data are plotted in Figure 5.4 for stringers 19L, 1L, and 19R. KHI argued that the data were suspect due to the possibility of mispositioned measurement features.

A tooling request was submitted in August of 1997 to check the positions of the primary station locators and the HVC measurement points. In October a report from tooling revealed that all features on FAJ 1 were within tolerance (+/-0.012) based on laser tracking coordinates. FAJ 2 had still not been verified at the time the internship ended in December.

It should be noted that Figure 5.4 shows overall excess panel length from the forward to the aft end. Final body join is most concerned with aft end panel protrusion beyond nominal. Table 5.4 shows that panel station deviation in the aft direction is slightly less than the total excess length implying a small forward bias in indexing. This point is subtle but important because if the panel lengths are corrected to nominal overall but the build process causes a shift forward, the aft end will then be short of nominal due to the forward bias.

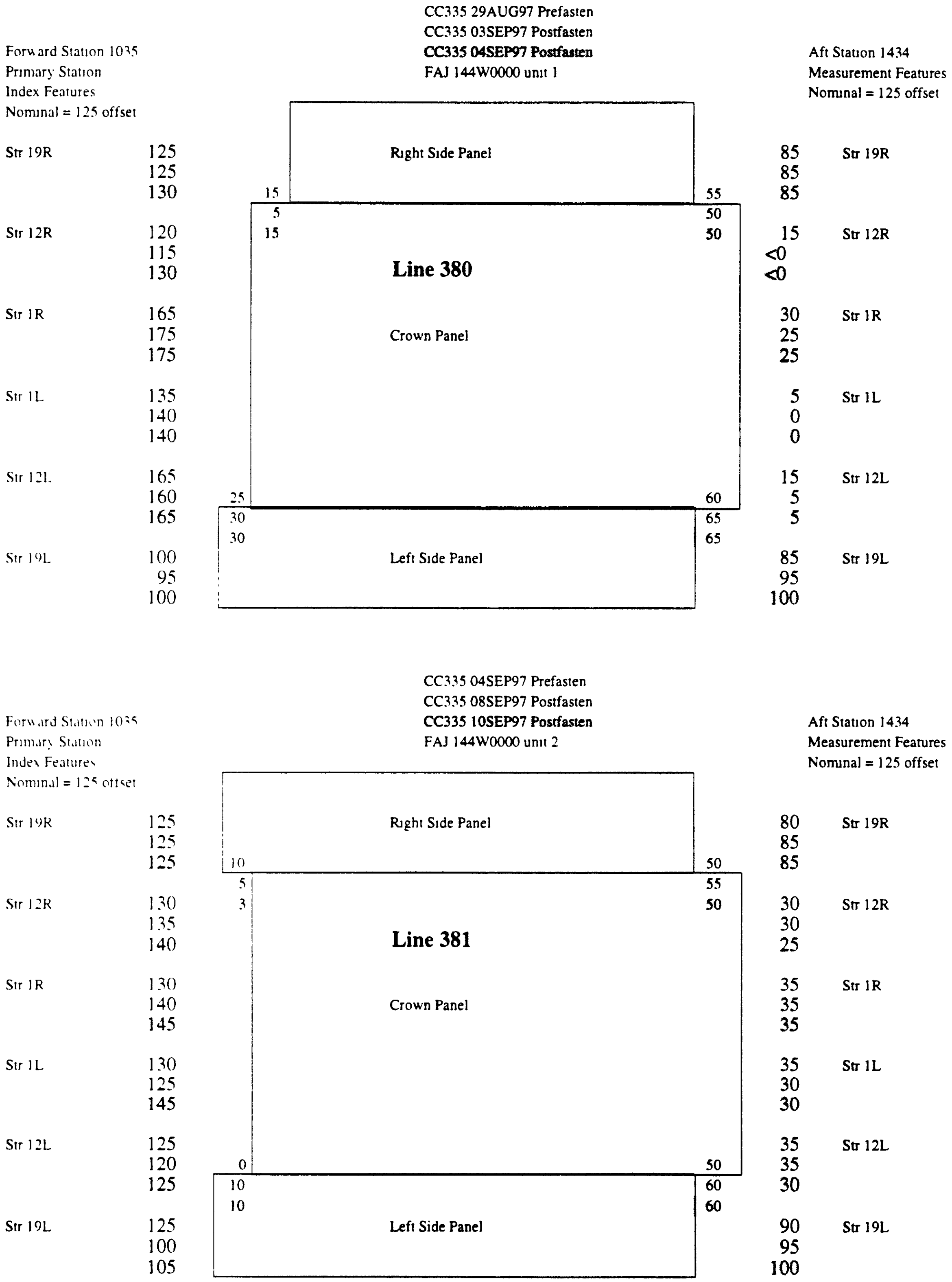
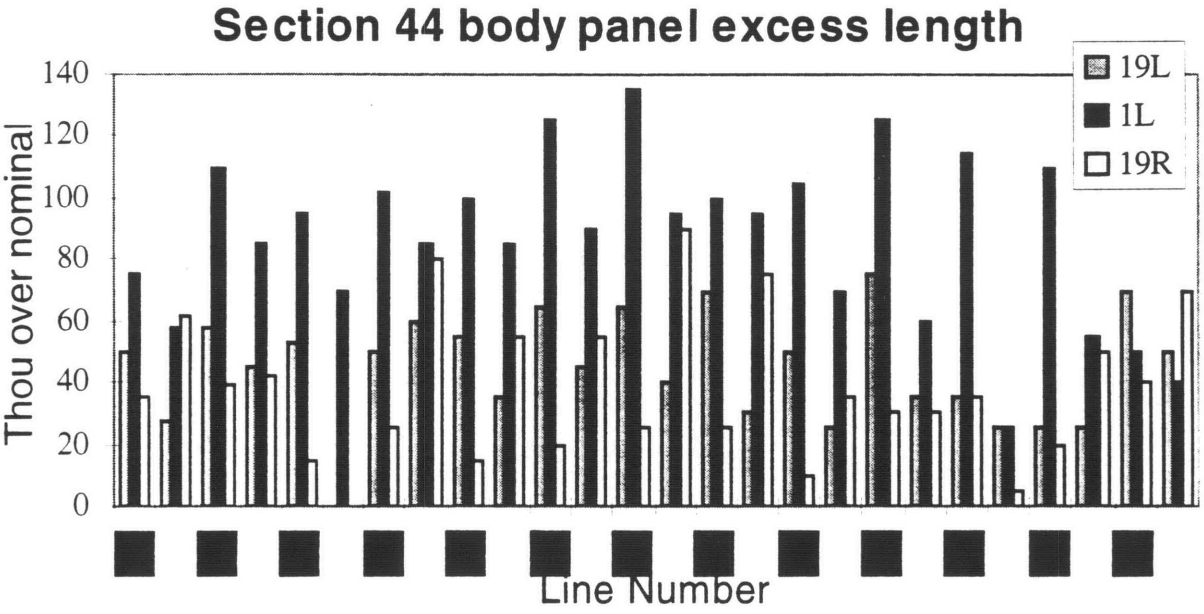


Figure 5.3 Section 44 body panel offsets relative to CC335 FAJ indexes (nominal = 0.125)



[redacted]

Figure 5.4 Section 44 body panel excess length based on CC335 FAJ features

The data in Figure 5.4 show an odd/even association pattern that may indicate a bimodal distribution. Table 5.4 shows that the measurements seem to differ between FAJ 1 and FAJ 2 and that the standard deviations are smaller when FAJ to FAJ variability is removed by breaking the data into odd and even groups. It is worthwhile to ask whether or not the differences are statistically significant because KHI trims section 44 body panels in one FAJ (see Chapter 6 for a datum flow chain analysis of the assembly process). This means that if there is an odd/even pattern, it is probably due to measurement differences between the two FAJs in CC335.

Breakdown of FAJ measurement data for L/N 379 through L/N 404 (inches from nominal)			
	Stringer 19L	Stringer 1L	Stringer 19R
Total excess length for all airplanes in both FAJs	46	89	38
Standard Deviation	16	26	22
FAJ 1 only (odd line numbers 379-403)	55	104	26
Standard Deviation	14	22	10
FAJ 2 only (even line numbers 380-404)	37	70	54
Standard Deviation	11	22	24
Aft station protrusion beyond nominal	33	84	33
Standard Deviation	12	19	24

Table 5.4 FAJ measurement data

5.1.3.1 Significance tests for differences in CC335 data between FAJ 1 and FAJ 2

The author assumes that panels measured in FAJ 1 and FAJ 2 in CC335 are drawn from the same normally distributed population and therefore have the same means and standard deviations. This is reasonable since KHI produces odd and even numbered airplane panels on common lines. A test of the hypothesis that there is a difference in measurement between FAJ1 and FAJ2 is desired. Accordingly the test statistic is:

$$t_{(\nu 1+\nu 2)} = [(X_1 - X_2) - (\mu_1 - \mu_2)]/s_{(X1 - X2)}$$

Based on the assumption of a single population of panels, $\mu_1 - \mu_2$ is zero. The symbol ν equals the degrees of freedom which is the sample size less one for each sample group. The pooled variance is:

$$s_p^2 = (\nu_1 s_1^2 + \nu_2^2 s_2^2)/(\nu_1 + \nu_2)$$

so that $t_{(\nu 1+\nu 2)}$ is given by:

$$t_{(v1+v2)} = (X_1 - X_2)/[s_p(1/n_1 + 1/n_2)^{1/2}]$$

For the left side panel and data in Table 5.4: $s_p = 12.58$ and $t_{(v1+v2)} = 3.64$. Level of significance for a two tail test at 95% confidence from the t distribution is $t_{24,0.05} = 2.06$. Thus, since $t_{(v1+v2)}$ is greater than the critical value we conclude that the measurement systems are different. The maximum listed confidence for a two tail test is 99.5% with a critical value of 3.09. Since the test statistic for the left side panels is greater than this it is fairly certain that the difference between the two set of measurements is not the result of stable random variation effects. A reasonable conclusion is that the measurement systems differ due to offsets in the tooling features.

For the crown panels $t_{(v1+v2)} = 3.94$ and the measurement systems differ. Finally, for the right side panels $t_{(v1+v2)} = 3.88$ and again the panel measurement systems differ.

The significant difference in measurement data sets is an important clue that something is wrong. The author did not recognize this during the internship, in part because the odd-even pattern took time to develop amidst other process noise. Several months later, Boeing Process Engineers discovered that measurement features on both FAJs were mispositioned (see Section 7.2).

5.1.5 Growth of body panels during assembly operations

Whether or not the excess length may be due to panel growth during drilling and riveting operations in CC335 is a reasonable question. Data of the type shown in Figure 5.2 and Figure 5.4 were collected before and after panel integration on each airplane in the study (about forty airplanes for lap misfair as in Figure 5.1 and thirty airplanes in the CC335 FAJs as in Figure 5.2). Steel tape data were also obtained before and after assembly on the airplanes listed in Table 5.2. A statistical comparison of the before and after data was not performed but the following qualitative statements are made:

- Forward and aft sliding of the panels relative to one another was often observed between pre and post integration. The reasons for this were discussed in Section 4.3.4.

- The relative part-to-part mismatch between crown panel and side panels (data of the sort shown in Figure 5.2) did not change by a noticeable amount. Recall that the measurement error for this check was estimated in Section 5.1.1 as +/- 0.010 inches.
- Steel tape measurements showed no change. The measurement error for this check was estimated in Section 5.1.2 as +/- 0.040 inches.
- Overall panel length (data of the sort shown in Figure 5.4) did not change appreciably. The reader may confirm this by examining Figure 5.3 which is typical of the thirty airplanes measured. Sometimes panels appeared to elongate slightly and other times they appeared to contract. Changes were typically around 0.005 inches and directionally inconsistent. Recall that the measurement error for this check was estimated in Seection 5.1.3 as +/- 0.012 inches.

The author believes that a detailed statistical study of the effect of integration is worth performing only for the sake of completeness. It is further opined that integration effects on panel length are much smaller than measurement error and length changes due to the relatively minor fluctuations in factory air temperature.

5.2 Analysis of Final Body Join Data

This section describes three data sources available in final body join used to further diagnose the problem. These are QA data, HVC data, and laser alignment system data.

5.2.1 Final Body Join QA data

On each airplane CC131 QA inspectors record key features for the forward and aft joins. These data include:

- WL 200 based on laser targets
- Seat track LBL 11 BL based on laser targets
- Seat track station gaps
- Outside skin surface skin to bulkhead gaps
- Keel beam BL
- Skin station gaps

The QA measurements are similar to the KCs recorded by the HVC system per UMED 40 that were discussed in Section 3.1.1 except that:

- QA checks are performed by trained QA inspectors whereas HVC jobs are performed by mechanics for whom the demands of maintaining production rate compete for attention.
- QA is directive in nature and drives NCR and MRB activity whereas "nonconforming" HVC measurements may go unchecked for long periods of time (see, for example, Figure 4.6).
- There are some technical differences in the exact location and types of measurements taken between QA and HVC in FBJ. For instance, HVC does not measure seat track station gap but takes skin station gaps at many more locations than does QA.
- QA requirements determine the final positioning of the body sections because failure to meet QA tolerances results in non-conformance reject activity which must be corrected. On the contrary, failure to meet HVC requirements often does not carry any immediate consequences. In spite of the laser alignment system, final body join mechanics and supervisors maintain that most joins are set to align features of the airplane (skin and seat track gaps) in order to obtain QA approval. Typically, body sections are brought together using laser alignment, adjusted as necessary to obtain QA approval, and final laser alignment data are recorded and accepted as given.
- QA requirements are pragmatic in that they inspect features that are observable to customers or necessary to ensure aircraft integrity or safety. HVC measurements, on the other hand, often measure abstract things such as distances to points in space that are not directly related to airplane parts. The selection of LBL 11 and WL 200 as primary BL and WL datums in the 777 program helps to address this issue

The point of the distinction between QA and HVC is that QA represents a data source with significant credibility and authority that HVC unfortunately lacks. For the purposes of this analysis, QA seat track and skin station gap are relevant. Figure 5.5 shows skin station and seat track LBL 11 station gap deviation from nominal.

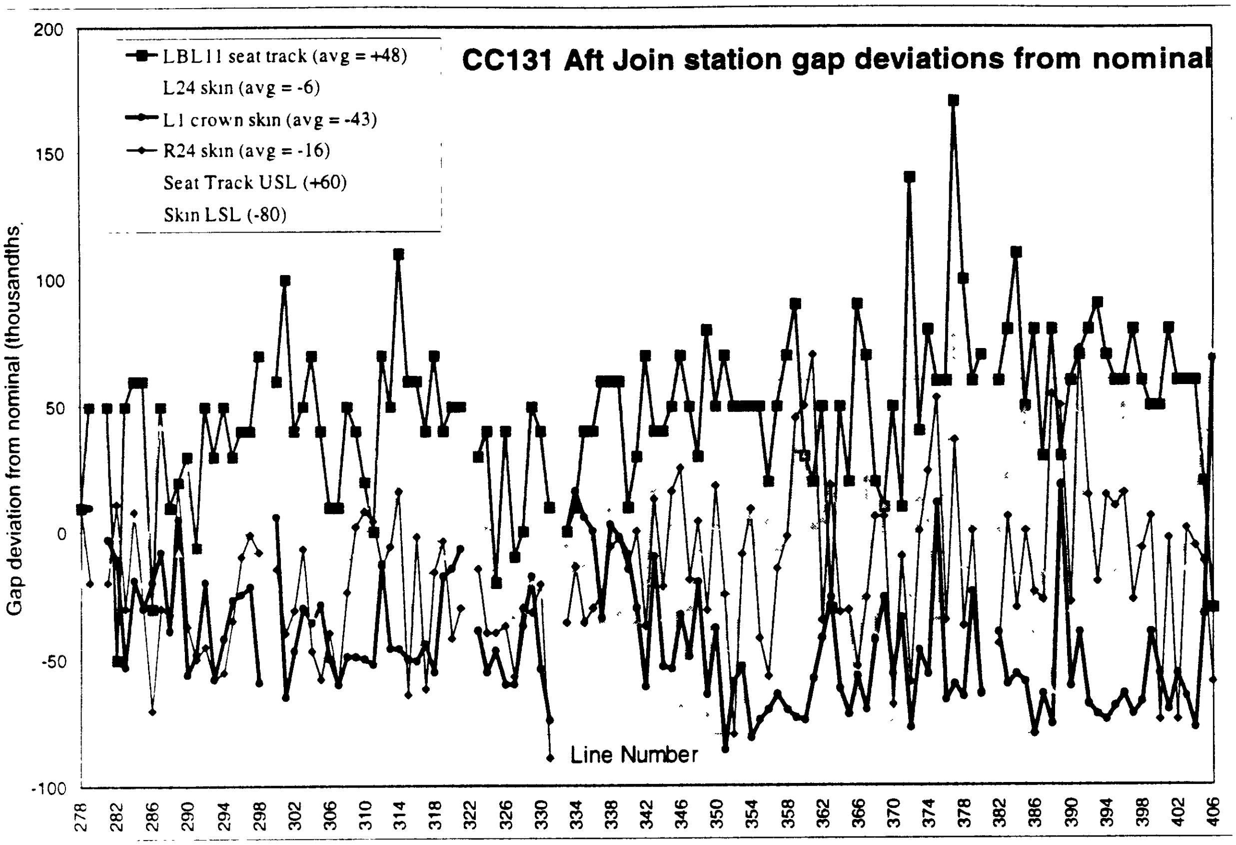


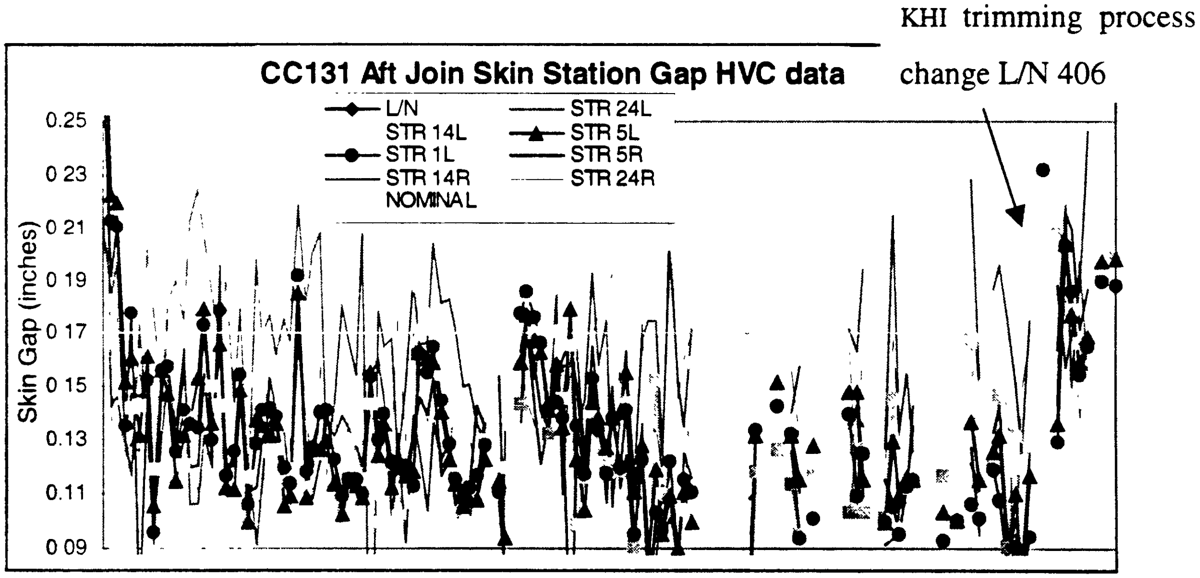
Figure 5.5 Aft join seat track and skin station gap deviation from nominal per QA records

Figure 5.5 data were obtained from QA records in CC131 (final body join). The specification for seat track station gap at LBL11 is 2.00 +/- 0.060 and 0.170 +/- 0.080 for skin station gap. In Figure 5.5 if, on a given join, the seat track gap were measured at 2.00 inches and the skin gaps were 0.170 inches all of the points for that airplane would plot on zero since none of the features deviate from nominal. Typically, however, seat track gaps average about 2.05 hence the blue line plots at +50 because the deviation from nominal is 50 thousandths (too wide). Likewise, crown panel skin staion gap typically measures around 0.125 so points are plotted at -35 because the crown skin station gap is 35 thousandths tight of nominal (0.125 - 0.170 = -0.035 = -35 thousandths). This said, the trend in Figure 5.5 shows that crown and side panel station gaps run tight relative to the LBL 11 seat track gap and have done so since the program's inception.

If the gap deviations from nominal that are plotted in Figure 5.5 are due to excess length of the section 44 body panels then the calculated excess lengths would be the difference between the LBL 11 seat track gap deviation and the skin gap deviation. For the left, crown, and right side panels these numbers are 0.054, 0.091, and 0.064 inches respectively. The point of this discussion is that excess length of the section 44 body panels by the amounts discussed earlier in section 5.1 are consistent with the condition of the aft join as measured by final body join QA inspections.

5.2.2 Final Body Join skin gap HVC data

Final Body Join HVC data for skin station gap in Figure 5.6 are similar to the QA data in Figure 5.5 except that the HVC data give more points around the airplane circumference. HVC and QA data in Table 5.5 are virtually identical. The side panels are tighter and less variable at stringer 14 than at stringer 24. Thus, QA data may understate the effect of an excess length condition by measuring only at stringer 24 on the side panels. The crown panel appears uniformly gapped based on HVC measurements at stringers 5L, 1L, and 5R. All skin gaps are consistently smaller than of nominal until L/N 406 at which point a vendor level change to the section 44 body panel length trimming process was made.



KHI trimming process change L/N 406

Figure 5.6 CC131 Aft Join Skin Station Gaps

Summary of CC131 Aft Join HVC Skin Station Gap Data (QA data shaded)										
	Left Side Panel			Crown Panel				Right Side Panel		
Stringer	24L	24L (QA)	14L	5L	1L (QA)	1L	5R	14R	24R (QA)	24R
AVG All 777s	0.161	0.163	0.132	0.133	0.128	0.130	0.130	0.128	0.154	0.145
STD DEV	0.040	0.028	0.035	0.033	0.025	0.034	0.028	0.027	0.031	0.026
AVG last 50 777s	0.154	0.161	0.115	0.120	0.116	0.113	0.117	0.115	0.164	0.155
STD DEV	0 028	0.033	0.020	0.020	0.022	0.021	0.021	0.023	0.036	0.029
AVG post chg	0.183		0.197	0.187		0.181	0.200	0.206		0.162
STD DEV	0.030		0.029	0.035		0.031	0.032	0.035		0.018

Table 5.5 CC131 HVC and QA Aft Join Skin Station Gaps (spec = 0.170+/-0.080)

Table 5.5 shows the average final body join skin gaps for the aft join based on HVC measurements (and QA measurements shaded). The set of all 777s includes roughly the first 120 airplanes built. The last 50 777s includes the fifty most recent 777s before the KHI process change. The post change figures are for ten airplanes after L/N 406 (see Figure 5.6). Notice the process shift toward nominal with a slight overshoot.

For the QA data shown in table 5.5, the LBL 11 seat track station gap averaged 0.046 too large This is what one would expect if the body panels are too long. Interference at the skin gap prevents the seat track gaps from closing to nominal. On L/N 133 KHI shifted the crown panel aft end trimming location by 0.075 shorter. This change is reflected in the FBJ HVC data shown in Figure 5.6 and Table 5.5.

5.2.3 Final Body Join laser alignment data

In practice airplane sections are aligned to gain QA buyoff for skin gap and seat track gaps and airplane alignment is either taken as given or best fitted using the laser alignment system in conjunction with QA requirements. Since the 777 alignment is based in large part on hardware features, dimensional variation in seat tracks, frames, floor beams, and panels feeds into airplane alignment. These hardware features are in turn determined by both vendor supplied parts and upstream build processes. Final Body Join operators give the laser alignment system high marks for its ability to join, pivot, and manipulate airplane body sections but the over-constrained nature of the final body join process and the conflicting requirements to satisfy both QA and the laser alignment system are often a point of contention.

Laser alignment data provided by Final Body Join allow one to make several interesting observations. Limited data were (only up to L/N 343) available in the HVC custom extract data base so a first observation is that difficulty in obtaining the data is a barrier to its effective utilization. This theme recurred often during the project. Once the data were obtained they needed to be separated and sorted to be of any use at all. With Microsoft Excel this process took several hours because airplanes were grouped by effectivity rather than line number and the data were "stacked" in a column nearly two thousand cells down. The effectivities for each point had to be first related to their corresponding L/N. After this the column had to be broken apart into a table with a row corresponding to a given L/N. Next an excel sort by L/N was performed to put the airplanes into a chronological sequence. After this the data were ready for plotting or interpretation. The point is that the format of data storage militates against systems level analysis and interpretation.

Figure 5.7 and Figure 5.8 show the result of the above manipulations for WL 200 and LBL 11. For WL 200 it is apparent that the most recent deviations from nominal are at STA 1845 which is due to FBJ manipulating the after body WL to meet skin gap and seat track QA requirements. The HVC data base lists an engineering specification of +/- 0.03 for the laser measurement and it is apparent that the process is not capable of meeting it. The reader is referred to Figure 2.1 for a diagram of major body sections and station locations. It is easy to demonstrate that the tail depression measured by the laser tracker at station 1845.5 (given that the pivot point is the section 44/46 body joint at station 1433) equates to a drop of the tail at the aft-most point on the airplane (STA 2570) equal to 2.75 times the values shown in the plot. Thus the maximum deviations are 0.4 to 0.5 inches at the tail. Note also that the top of the crown skins are located at WL 340 so the skin gap effect of the deviations shown in Figure 5.7 is (340-200)/(1845.5-1433) = 0.339. Thus the skin gap opens by about one third of the deviation shown in the figure which puts the maximum skin gap effect of moving the tail at around 0.050 inches to 0.060 inches. This assumes that the pivot point is the seat tracks. If the pivot point is taken at the crown skins then the seat track gap can be closed by 0.050 inches while the skin gap remains constant.

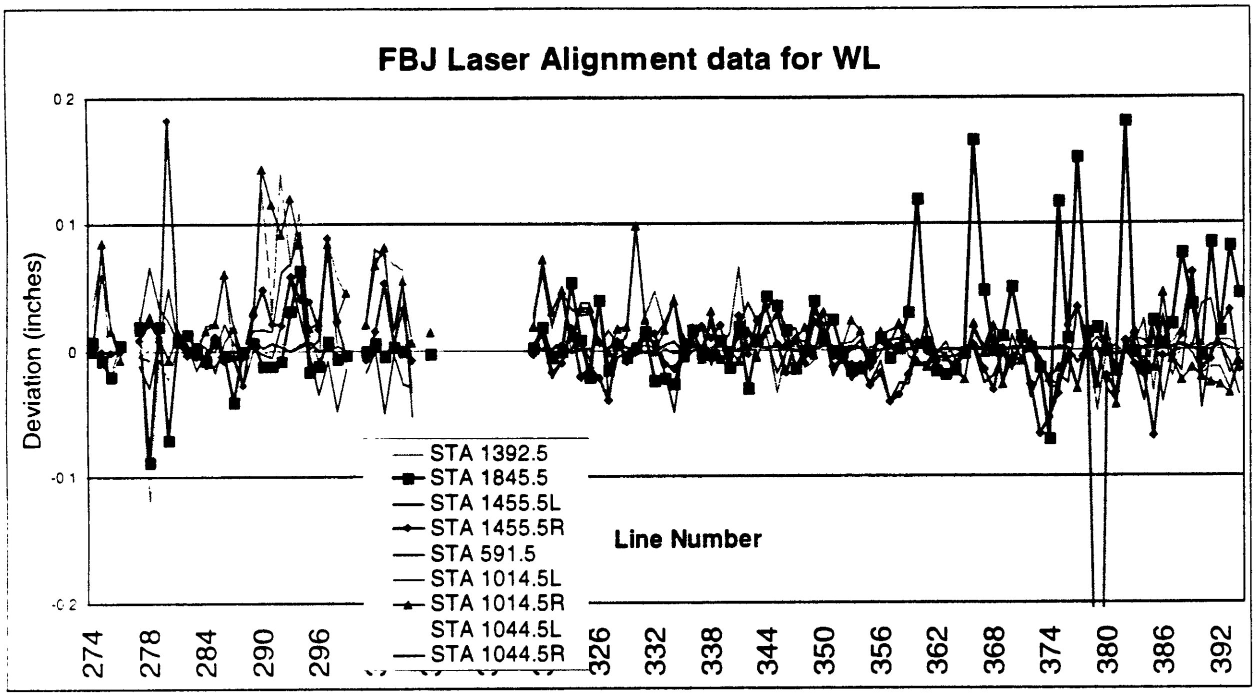


Figure 5.7 FBJ Laser Alignment data for WL 200. Positive deviations are downward

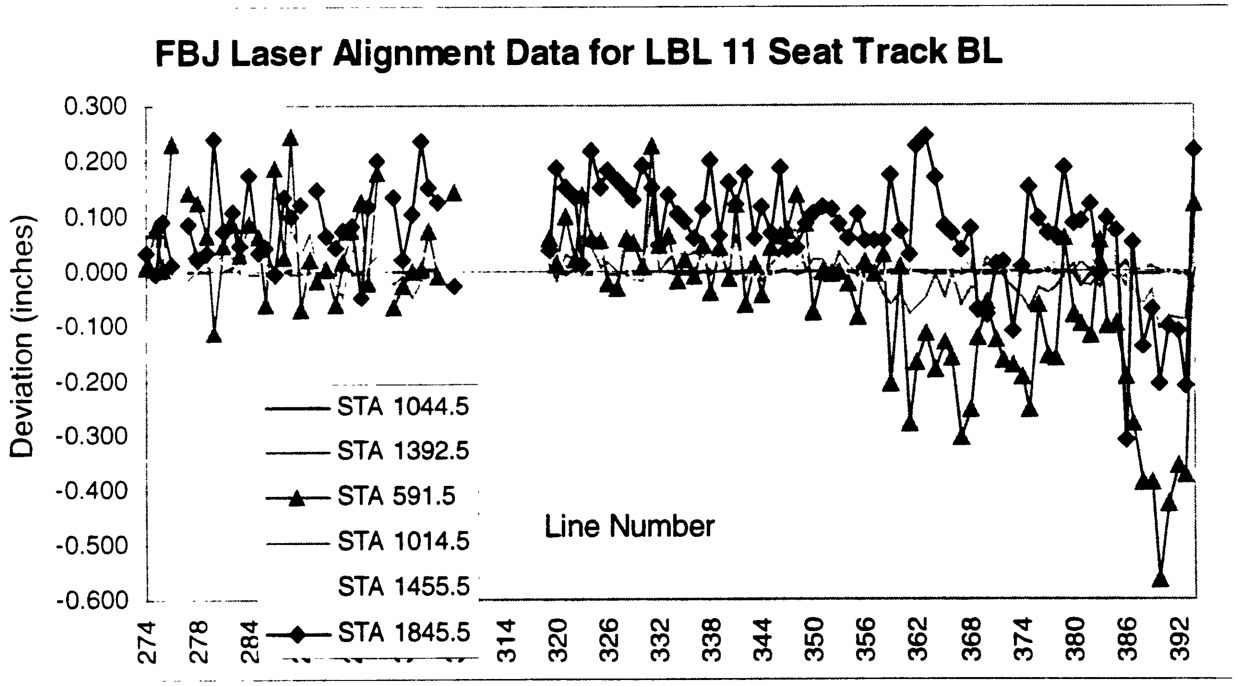


Figure 5.8 FBJ Laser Alignment data for LBL 11. Positive deviations are to right side

Data for LBL 11 alignment are shown in Figure 5.8. It is interesting that the deviations for left and right alignment are larger than for WL 200. Final Body Join personnel maintain that they build a straight airplane and that this error may be due to the measurement of BL which occurs at a point 55 inches elevated from WL 200 due to the configuration of the temporary laser targets used. The largest deviations are on the nose and tail (STA 591.5 and 1845.5) and are mostly positive for both the forward and aft sections early in the program. Around L/N 356 the pattern changed and the tail is to the right more often and the nose is to the left.

Data in Figure 5.8 can be used to calculate the potential effect of the alignment on airplane performance based on a study in 757 as follows[17]: "Aerodynamics evaluated the drag penalty associated with misalignment of the 757 body due to either the 43/44 or 44/46 join. Misalignment results in rolling and yawing moments which must be trimmed out during flight with continuous deflections of the aileron and the rudder. The deflections cause increased fuel burn and drag. If the body is joined such that the gap in body skins (assuming the body section skin edges of both pieces are on clean station lines) is 0.060 on one side and 0.300 on the other then the body would be misaligned 0.10 degrees.

This would result in the following penalties:

Equivalent operating empty weight (EOEW):	44 lbs
Increased fuel burn per year based on 13,001,000 nm mission per year:	690 US gallons

Typically aerodynamics assessed rejection tag items having an EOEW of less than 7 lbs. as being aerodynamically insignificant."

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[17] Interoffice memorandum from Gerard Figurelli of Boeing Aerodynamics Engineering Support Group to Richerd Matros of 777 Process Engineering dated 18SEP97.

An EOEW change of 44 lbs. equates to 690 gallons of incremental fuel consumption. Thus Boeing's threshold of a seven pound change in EOEW translates to about 110 gallons of incremental fuel consumption per year to the airline customer[18].

How do these findings apply to 777 body manipulations? The largest WL 200 deflection on any 777 airplane (Figure 5.7) to correct a skin gap seat track gap condition was on L/N 381. At STA 1845.5 the drop was 0.181 inches corresponding to an angular deflection of 0.181/412 x 360°/2π = 0.025°. If one considers a left side gap at the minimum tolerance 0.170 - 0.080 = 0.090 and a right side skin gap at the maximum tolerance 0.170 + 0.080 = 0.250 then the angular deflection is 0.035°. Likewise if one considers a crown panel skin gap at the minimum and a seat track gap at the maximum the angular deflection is 0.057°. Assuming that the fuel burn penalty scales to the second power with angle (based on Bernoulli's equation for drag so that cutting the angle deflection in half reduces the drag penalty by a factor of 4) then one can conclude that nominally built 44 and 46 sections joined to the worst case QA requirements would result in a EOEW penalty of 44 x $(0.057/0.10)^2$ = 14 lbs. which is slightly above the maximum aerodynamics allowed of 7 lbs. For left/right alignment the penalty is 44 x (0.025/0.10)2 = 2.5 lbs. which is well below the maximum allowed. It is important to point out, however, that the 757 study was based on left/right misalignment and it was stated in a follow up meeting with Mr. Figurelli in attendance that WL angular deflections resulted in much lower penalties. Laser alignment WL deflection data in Figure 5.7 reveal a maximum tail deflection of 0.025° to control gaps within QA requirements. Thus the skin gap tolerances (or features of the airplane based on QA) seem adequate to prevent aerodynamic penalties for nominally built body sections as far as the WL data are concerned.

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[18] According to the Boeing web page (http://www.boeing.com/commercial/757-200/background.html), a 757-200 has a range of 4,520 statute miles (4,000 nm) and a fuel capacity of 11,276 gallons. Assuming the aircraft lands with 20% fuel remaining, the 13,001,000 nm per year mission requires about 30 million gallons of fuel. This means that reject tags are assessed against items that change fuel consumption by $110/(30x10^6)$ = 0.0004%.

For the BL data shown in Figure 5.8 the largest nose deflection is 0.567 inches on L/N 390 which equates to an angular deflection of 0.567/(1035-591.5) x 360°/2π = 0.073°. The angular deflection required to correct the worst case skin gap condition of 0.080 inches on each side is 0.160inches/(22ft x 12 inches/ft) x 360°/2π = 0.035°. In terms of correcting skin gaps it is difficult to imagine why a deflection as large as 0.567 inches would be necessary. In terms of fuel burn penalty 0.567 inches equates to an EOEW of 44 x $(0.073/0.1)^2$ = 23lbs. (which is well into the reject region). The 0.567 inch deflection also corresponds to a difference in skin gaps from left to right of (0.160/0.026) x 0.073 = 0.45 inches. Examination of the forward join QA records for this airplane, however, indicate that the actual difference was only 0.006 between skin gaps at stringers 24L and 24R (i.e. 24L was at 0.167 and 24R was at 0.161). There is no physical reason why BL deflections as large as those shown in Figure 5.8 should occur and that if they are occurring there is an associated fuel burn penalty. Another possibility is that the laser alignment data for BL deflection have a large measurement error due to the configuration of the temporary target system.

Despite the fact that final body join personnel knowingly lower the tail of the airplane the BL offsets are larger and more variable than those due to WL. Buttock line laser data do not match what would be necessary to correct even the worst case skin gap mismatch and are inconsistent with part to part skin gap measurements taken in FBJ. Figure 5.8 data for BL deflection are larger than what would be required to prevent drag penalties based on the 757 study (any deflection of the nose or tail in Figure 5.8 of greater than 0.297 inches left or right will result in an angular deflection of over 0.039° and will cause EOEW to be greater than 7 lbs.).

Airplanes built within QA tolerances will align straight enough to prevent drag penalties if the adjacent structures are built to nominal. It is obvious, however, that this is not always the case and that the body sections have many sources of variation accumulated through best fitting and rework. Thus, airplane features are not a robust proxy for airplane straightness and to the extent that laser data can be used as an in-process check it may be very valuable. Table 5.6 contains a summary the laser alignment data.

Summary of Final Body Join Laser Alignment data for airplanes built through 12/97									
Body Section	Forward Body			Center Stub (Monument)			Aft Body		
WL data at STA	591.5	1014.5L	1014.5R	1044.5L	1044.5R	1392.5	1455.5L	1455.5R	1845.5
Grand AVG	0.012	0.012	0.015	0.001	0.001	0.002	-0.005	-0.002	0.011
STD DEV	0.026	0.037	0.034	0.004	0.003	0.004	0.023	0.051	0.040
AVG of last 50 A/Ps	0.000	-0.006	-0.003	0.000	0.001	0.002	-0.008	-0.016	0.025
STD DEV	0.016	0.016	0.019	0.002	0.002	0.004	0.024	0.063	0.049
Body Section	Forward Body			Center Stub (Monument)			Aft Body		
BL data at STA	591.5	n/a	1014.5	1044.5	n/a	1392.5	1455.5R	n/a	1845.5
Grand AVG	-0.032	n/a	0.003	0.000	n/a	0.000	0.019	n/a	0.078
STD DEV	0.145	n/a	0.041	0.005	n/a	0.005	0.035	n/a	0.095
AVG of last 50 A/Ps	-0.119	n/a	-0.016	0.000	n/a	0.000	0.014	n/a	0.049
STD DEV	0.154	n/a	0.041	0.006	n/a	0.006	0.034	n/a	0.112
Positive deviations are downward deflections in WL and right for BL									

Table 5.6 Summary of final body join laser alignment data

5.3 Summary of Chapter

Informal measurements described in the beginning of this chapter presented evidence that section 44 body panels were consistently longer than engineering nominal. Final body join QA data reveal a characteristic that could be caused by section 44 excess body panel length. The final body join QA data also reveal that the aft join process mean for all three section 44 body panels is long relative to the LBL 11 seat track. The amount of deviation in the QA data from nominal closely matches the excess length measured in CC335. Final body join HVC data indicate that aft join skin gaps around the circumference of the airplane are smaller than nominal and this too is consistent with excess panel length by the amount measured.

Laser data show that airplane alignment absorbs body structure dimensional variation (particularly in the the aft join so that QA features remain within tolerance). The amount by which body alignment is adjusted seems insignificant in the WL direction. Buttock line laser alignment data show deflections that are aerodynamically significant based on the Boeing criteria of assessing NCR tags if EOEW exceeds 7 lbs. The BL laser alignment deflections, however, are large compared to skin and seat track station gap deviations observed in production and are inconsistent with final body join QA records. This dichotomy leads one to question the accuracy of the BL data.

The large deflections in the BL data shown in Figure 5.8 (which equate to over one half inch at the nose and tail and are often in opposite directions) may be due, in part, to measurement noise. Since this source of error is not quantified it is not possible to tell if 777s are straight or built with the nose shifted slightly to the left and the tail shifted to the right.

6. Chapter 6 - Datum Flow Chain Analysis

This Chapter utilizes tools developed at MIT[19] to study the problem from the standpoint of the flow of datums through the assembly process. The chapter borrows heavily from previous work by one Ph.D. student and one Master of Science student from the MIT department of Mechanical Engineering. The students studied the 777 forward join in Everett and the section 43 and 44 body panel assembly processes during a factory visit to KHI. A tutorial created by the students, Krish Mantripragada and Jeff Adams, from their Boeing trip report is given in 7.

6.1 Section 44 body panel assembly sequence

This section provides an assembly sequence overview of the steps in the section 44 assembly from one production site to the next. Details on the Everett assembly procedures and associated KCs were discussed in Section 3.1. The production assembly tree for the problem under study is shown in Figure 6.1. The problem arises when the 44 and 46 sections are joined in CC131. It should be clear that the problem with the join is one of integration between section 44 and section 46.

There is no evidence of a problem with the crown panel forward edge station of section 46 (the sides and crown panel at station 1434 are cut to net trim in CC328 after assembly) but the possibility is under investigation by Boeing engineers. The placement of the section 46 keel panel as a contributor to the short edge margin problem is also under investigation. Unfortunately for final body join operators, variation from both section 44 and section 46 washes to station 1434. Perhaps a better design would have been to wash variation in the same direction in all of the body sections so that double accumulation of variation is not absorbed in final body join as is the case with the aft join.

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[19] Mantripragada. R.; Whitney, D.; The Datum Flow Chain: A Systematic Approach to Assembly Design and Modeling. Paper to appear in Research in Engineering Design, vol. 10, no. 1, October, 1998.

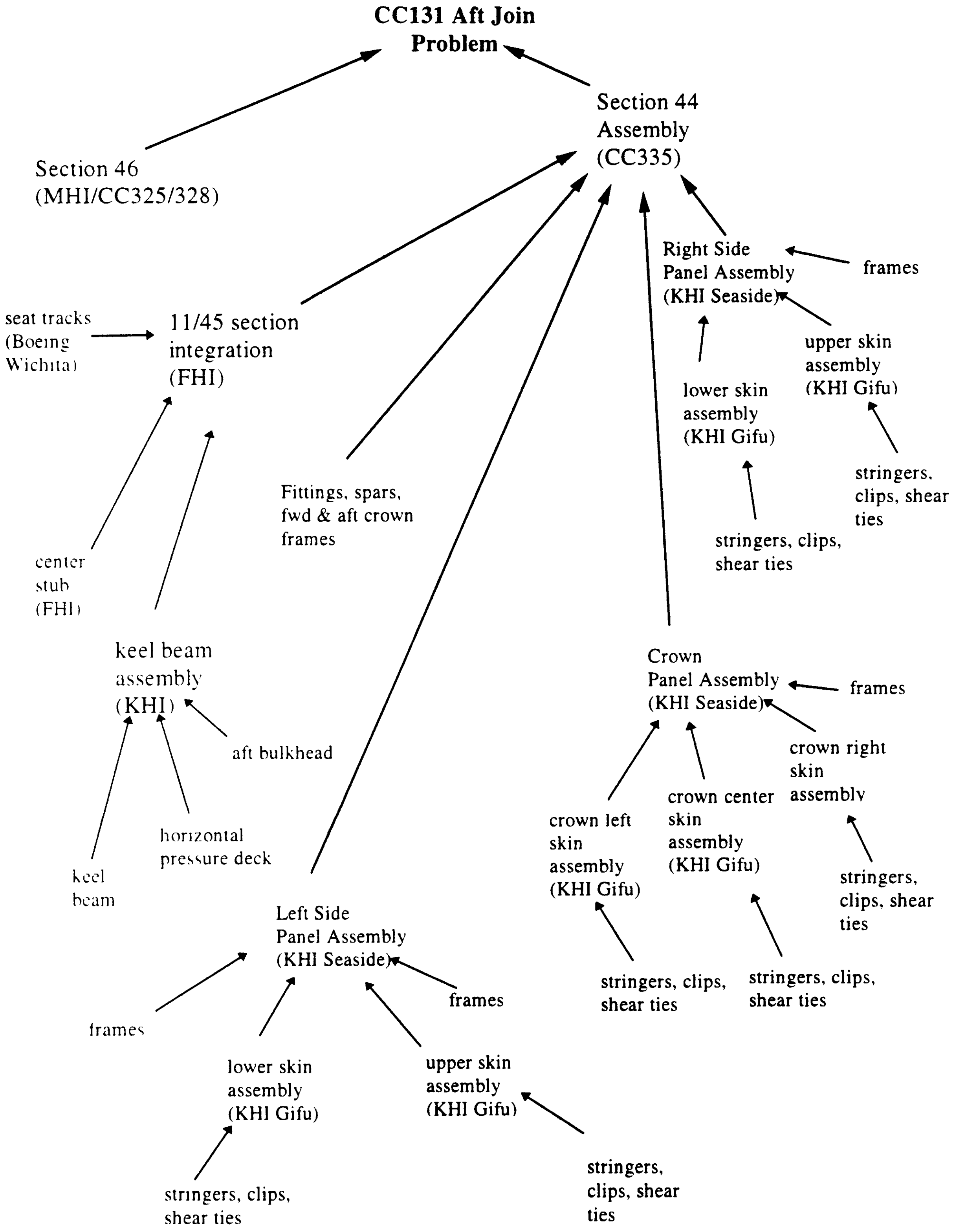

Figure 6.1 Assembly tree for section 44/aft join problem

Because the structures involved are large and compliant, requiring the use of rigid fixtures in remote locations from each other, small variations in the body structures are sometimes almost unobservable until mating parts are brought together in final assembly. Unfortunately, however, this is often the most difficult time and place to correct the problem. These considerations were discussed by Cunningham[20].

The author proceeds with a systematic mapping of the production chain from start to finish. The DFC is utilized to understand if and where problems might be likely to arise. If the DFC indicates that we should expect problems in a given area, this provides evidence that an earlier design stage consideration may have resulted in a more robust assembly. Ex-post this is of little value but if properly institutionalized in an organizational learning process it may benefit future derivatives or new products. On the other hand, absence of a DFC identifiable problem may allow ruling out of extraneous possibilities and facilitate a more focused search for root causes. Cunningham identifies five categories of mechanical assembly problems:

- tolerance stack up - all parts are within allowable engineering tolerance but the accumulated variation causes the assembly to be outside of specification limits. In this case the tolerances are incorrectly allocated. If the tolerances are based on refined manufacturing capability, however, it may be necessary to change the production process since the individual part variation is representative of the best the individual component processes can deliver. DFC methodology can be helpful in this regard as will be shown with frame mismatches in Section 6.1.2.
- design problem - the part's geometric design is incorrect. e.g. physical interference between parts, overlap, wrong tolerances, etc.
- part quality problem - the parts are manufactured out of tolerance.
- assembly process problem - a given step in the assembly process causes the problem. e.g. environmental conditions, poor procedures or compliance, mislocating in fixture, etc.

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[20] Cunningham, Timothy W., Migratable Methods and Tools for Performing Corrective Actions in Automotive and Aircraft Assembly, Thesis for the Degree of Master of Science in Mechanical Engineering, MIT, 1996.

- tooling or fixture problem - locating features are worn or mispositioned or the tool is incorrectly designed or installed.

While the DFC cannot explicitly solve all of these types of problems it will help provide insights as to where one might look and answer the question "what could have been done differently?"

6.1.1 Skin panel assembly sequence and indexing from KHI to Everett

This section discusses the general assembly sequence used by KHI to fabricate section 44 body panels. The subject problem is one of panel size as it pertains to the location of the aft skin edge. It is well known, however, that variation in frame station location and side panel attachment points to the center stub floor beams also feed into panel skin edge location. This is due to the best fitting practices described earlier. For this reason the details that set skin and frame station location are studied. Where indexing is important it is described using a DFC.

6.1.1.1 KHI Gifu Plant

Skin sub-panel fabrication, drilling, and assembly takes place at Gifu. Stringers, frames, shear ties, and skins are manufactured there. Shear ties are not considered critical in determining station constraints and are not considered. Thus the operations of interest to us are:

- NC drilling of stringer coordination holes and positioning of stringer clips
- NC drilling of skins
- Auto riveting of stringers to skin

Stringers are drilled and assembled on an automatic assembly machine. The sequence of steps is as follows:

1. Position stringer - the forward edge of the stringer provides the station index.
2. Drill holes - an NC located #40 diameter coordination hole is drilled with a stated accuracy of +/- 0.005. Pilot holes (#30 diameter) for subsequent stringer positioning to skin and stringer clips are drilled to +/- 0.005.
3. Position clips - clips are positioned to +/- 0.005 by NC function.
4. Insert rivets.

Skin section panels arrive preformed for contour and near net trim. The skin panel is indexed for station from the forward EOP into the bed of a large NC drilling machine. The machine controls the location and drilling of all holes to #40 diameter for attachment of stringers, shear ties, and neighboring skin panels. Stringer forward coordination holes are drilled to +/- 0.004 and other holes common to a stringer are located to +/- 0.008 inches.

Stringers are installed hole to hole with the forward #40 diameter coordination hole serving as the WL and STA index. Stringers are positioned by matching the forward most key hole (stringer coordination holes) and then set by aligning the #30 pilot holes on the stringer with the #40 holes on the skin. The stringers are temporarily fastened and then moved to an automatic riveting machine for drilling and riveting. The riveting pattern is an alternating forward to aft and aft to forward process. e.g. the first stringer at the origin of the machine is riveted from forward most hole to aft and then the adjacent second stringer is riveted from aft to forward and so on.

After riveting, inspection, manual installation of brackets, and sealing are performed. The skin subassembly panel is then packed and shipped to the Seaside plant. A datum flow chain for the Gifu operations is shown Figure 5.2. Letters in parentheses, e.g. (a), (b), etc., indicate the sequential position of the assembly step shown.

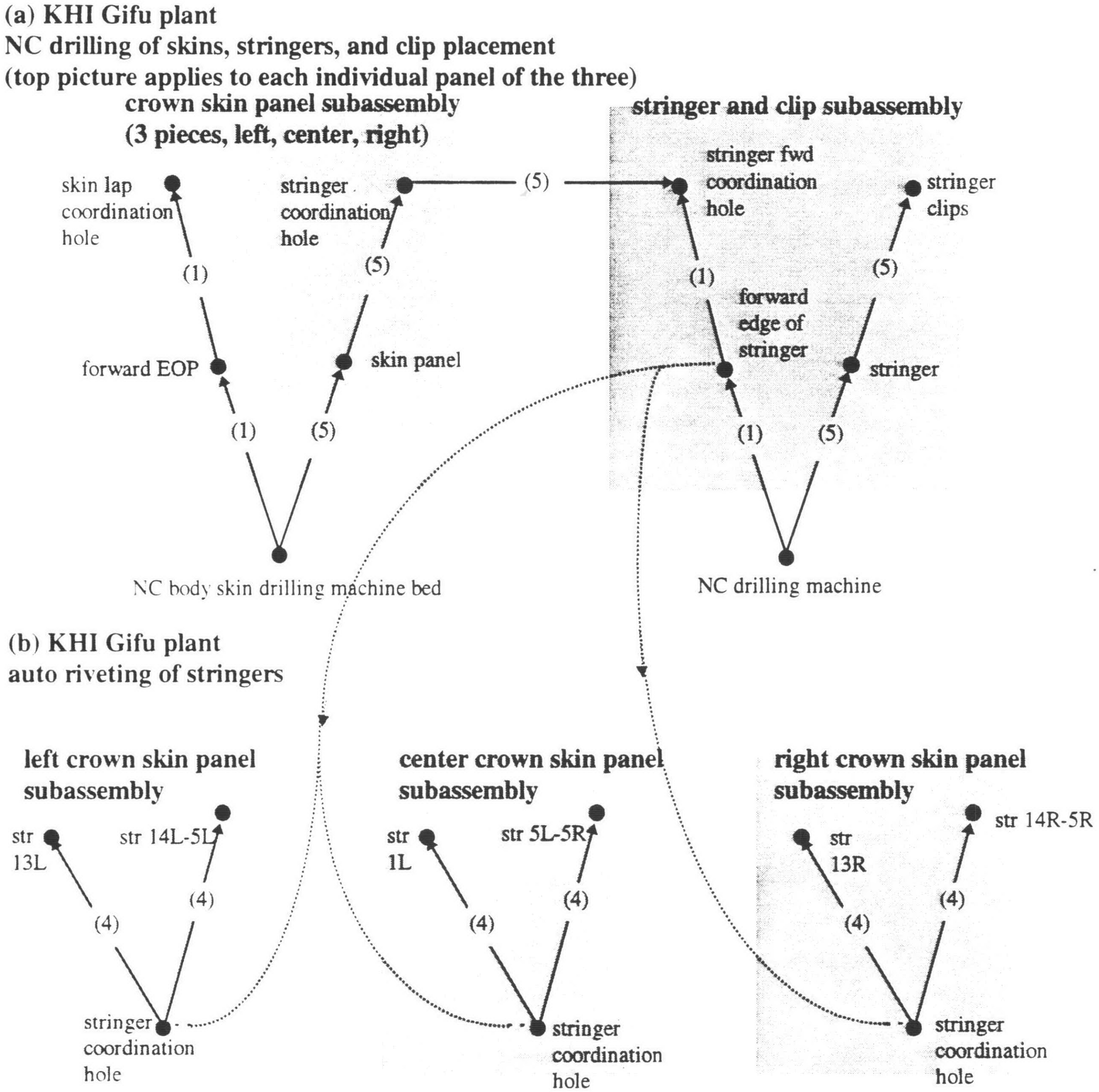


Figure 6.2 Datum flow chain for KHI Gifu plant crown panel subassemblies

6.1.1.2 KHI Seaside Plant

At KHI's Seaside plant the skin panel subassemblies are fastened to one another, the aft skin edge is trimmed to nominal, and circumferential frames are attached. Frame attachment, although not part of the original internship project, is included in the datum flow chain representation. The reason for this is that as a result of mapping the DFC for aft skin edge it was discovered that an over-constrained condition exists in frame attachment and that frame mismatch may be at least partly caused by the datum flow sequencing and attendant variation stack-up.

Seaside assembly begins with the loading of stringers common to a skin lap into a rivet assembly jig (RAJ), also called a picture frame. Skin panel subassemblies are removed from their shipping containers and set in place. Side subassemblies are loaded first and then center section (side panel assemblies consist of upper and lower side panel subassemblies). Side subassemblies are located to the RAJ using tool tabs which mate with adjustable indexes for clocking and BL and panel forward edge at stringer 13L and 13R for STA. The skin lap coordination holes are then enlarged to #30 diameter and the center panel is loaded and located using stringer 1L. Left and right subassembly panels are then adjusted by positioning the tooling tabs until the enlarged #30 skin lap coordination holes line up with the #40 skin lap coordination holes on the center subassembly. KC measurements are made at side EOP, aft EOP, and skin laps to check panel alignment.

Skin subassemblies are secured with belts and key stringers 13L and 13R are clamped. KC measurements are taken again and positions are fine tuned until KCs are within tolerance under the restrained condition. Coordination holes between skin panels and holes common to sub-panel splice area stringers and shear ties are back drilled for tack fastening. The panels are then disassembled, de-burred, sealed, reassembled, and tack fastened. The entire assembly is moved to an automatic riveting machine for final fastening.

Mantripragada and Adams made several astute comments concerning the RAJ process in their KHI trip report. Two are repeated here for emphasis:

1. There are conflicting indexes on the panel subassemblies in that panels are located to the RAJ and hole to hole causing an over-constrained situation. During the recent internship, clarification was sought from KHI as to which index was dominant. The vendor stated that the panels are located to the forward EOP for STA and at 13L, 1L, and 13R for clocking and

BL. The panels are then indexed hole to hole, and checked against RAJ features. Note that this still does not answer the question. The panels must either be indexed to the RAJ features or assembled hole to hole. Only a perfect set of parts with no variation could satisfy this over-constraint.

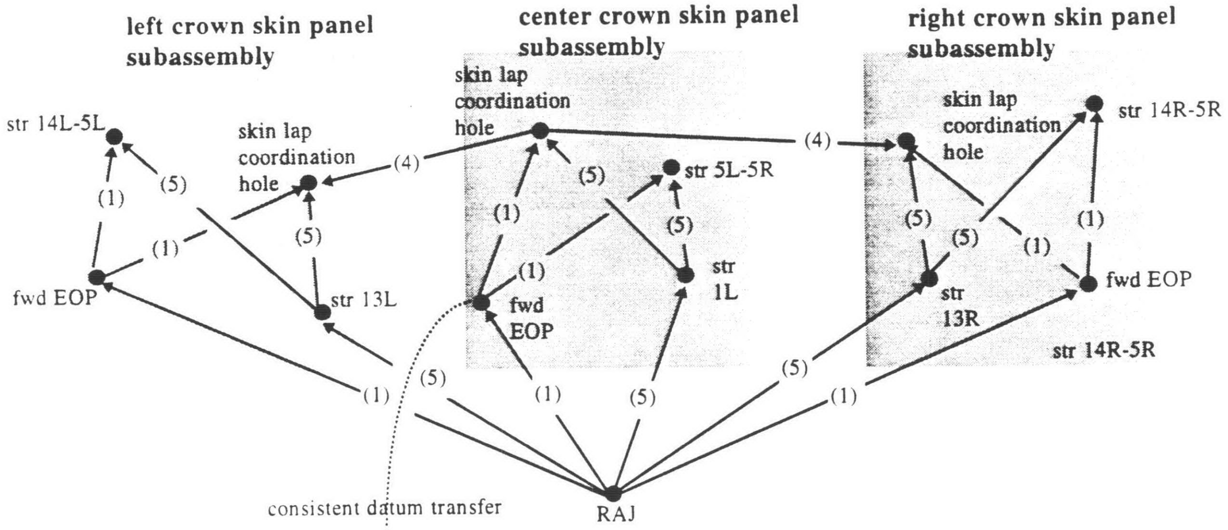
2. Fine tuning of the restrained assembly may induce pre-load affecting final shape.

Next the assembly is moved to the floor assembly jig (FAJ). Prior to its arrival the frames are loaded and indexed using three K-holes in the frames. The K-hole indexes on the FAJ have a net size hole that mates with the center K-hole and the outer two are slotted. The crown panel assembly is indexed at the forward EOP for STA and stringer 1L for BL and clocking. Stringer 13L and 13R also attempt to control positioning that is already set by stringer 1L and the contour header for WL.

Aft skin edge is trimmed to nominal while in the FAJ before frame riveting takes place. Frame location is checked against the FAJ but no shims were observed between any of the stringer clips and frames. This leads one to question how frame station is really determined. If frames are indexed to the FAJ and then securely fastened to clips whose station positions are subject to inherent variation, the assembly is over-constrained in the FAJ. When the assembly is removed, however, the frame location will adjust to that of the clips.

A DFC for the Seaside process is shown in Figure 5.3. Note that over-constraints in the RAJ sub-panel assembly process and in the FAJ frame installation step are clearly identified. DFC mapping during the process design stage would have identified these over-constraints as constituents of potential integration risk for final assembly before production operations started.

(c) KHI Seaside plant
RAJ assembly of subpanels



(d) KHI Seaside plant aft skin
edge trimming and frame installation

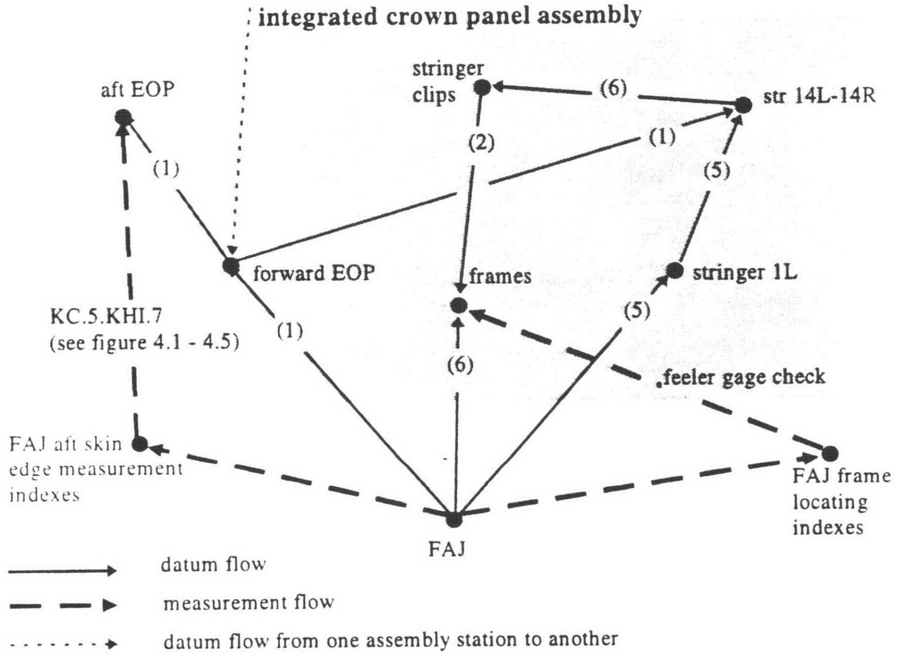


Figure 6.3 Datum flow chain for KHI Seaside plant crown panel assembly

6.1.1.3 Boeing Everett CC335

Body panels are indexed from FAJ features in CC335 according to the design build procedure discussed in Section 3.1. Side panels are set for WL and BL from laser targets at stringer 27 and STA from the forward EOP at stringer 19 per the load document. In practice mechanics use this as a first pass and then check for floor beam mismatch. This condition occurs at any of the seven points in the lower aft area of the side panel where it attaches to the center stub transverse floor beams. Side panels are then fine tuned +/- 0.030 to minimize floor beam shimming requirements. The crown panel is located for BL and WL off of stringer 1L.

The load document calls for double indexing crown panel station at stringer 1L both forward and aft. Note the impossibility of what this calls for operators to accomplish. They are thus forced to decide on their own what is most important and then act accordingly. In practice the crown is typically indexed at 12L and 12R from the forward edge and then fine tuned +/- 0.030 inches to match frame splices. A DFC for the CC335 design process is shown in Figure 6.4. The as-is process is shown later in Figure 6.6.

(e) Boeing CC335 assembly

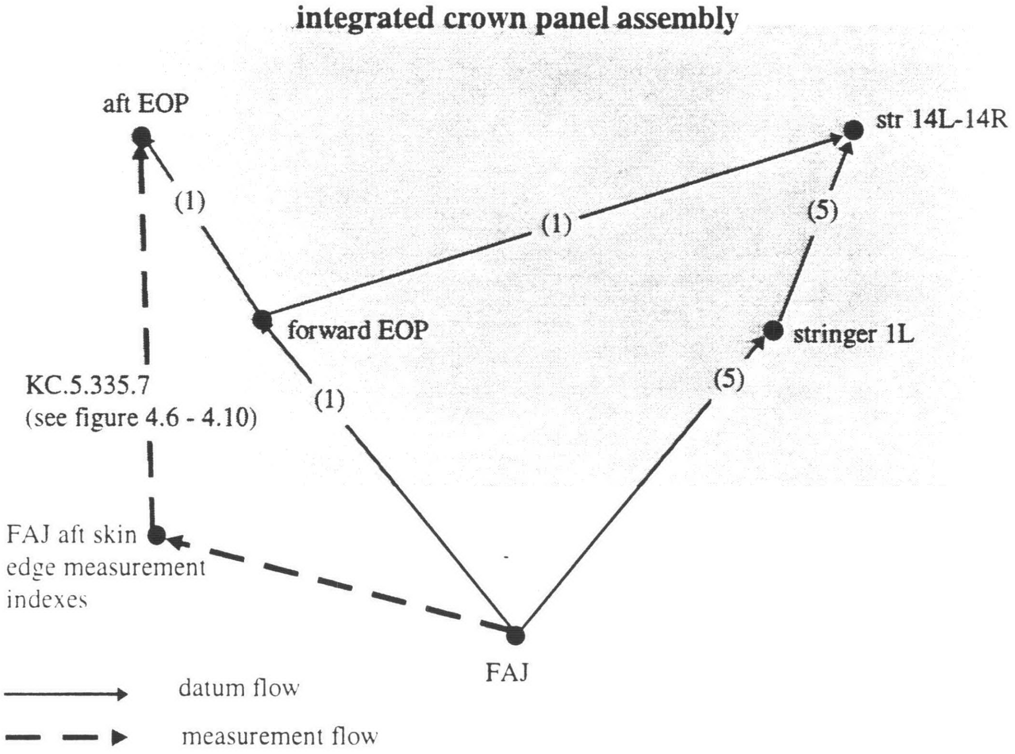


Figure 6.4 Design datum flow for Boeing section 44 crown assembly

6.1.1.4 Start to finish datum flow

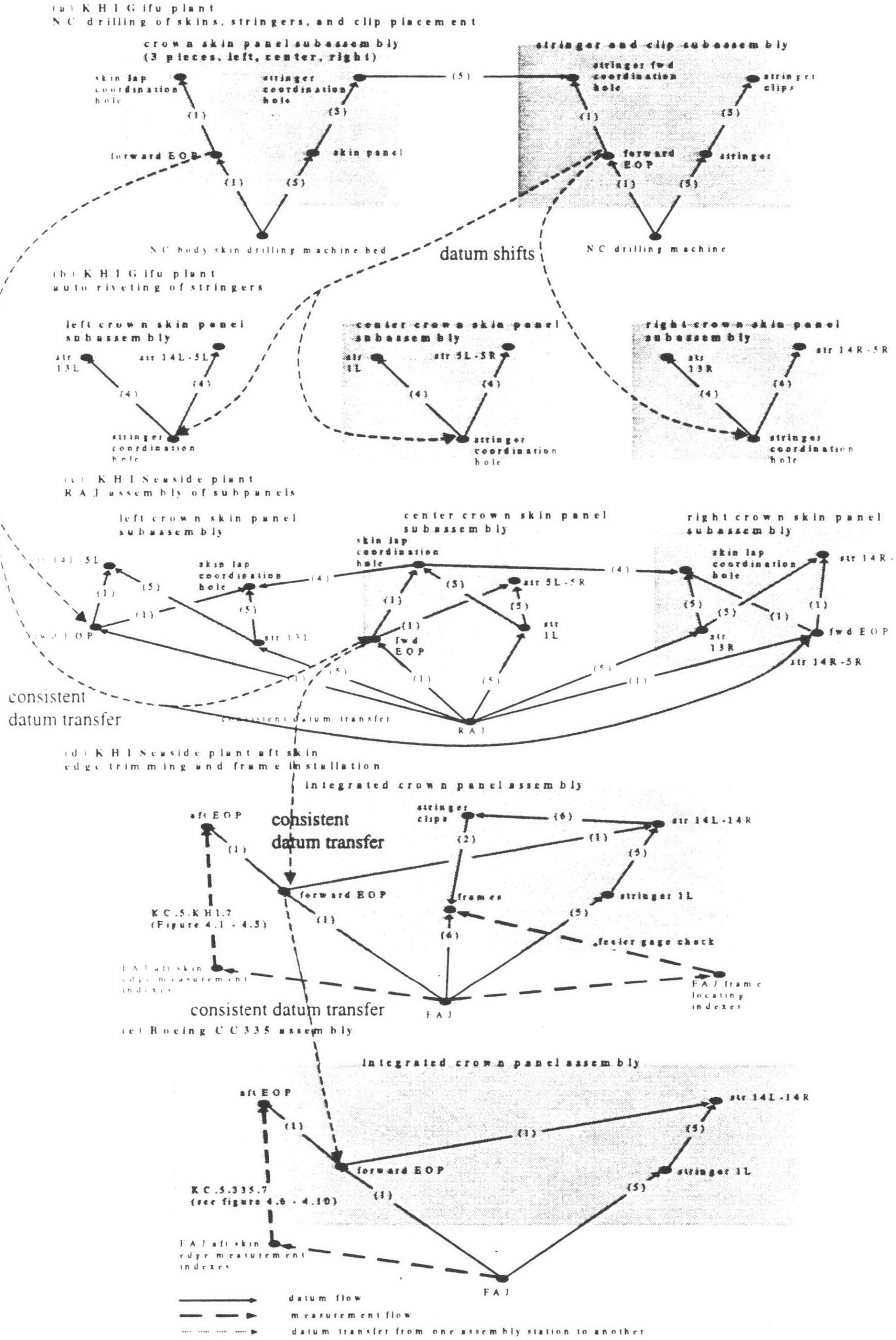


Figure 6.5 Start to finish datum flow chain for section 44 crown panel assembly

The individual datum flow chains are shown from the start of the manufacturing process to the finish in Figure 6.5. Datum flow for the aft skin edge is consistent in the as-designed process. The reason for the panel excess length problem must be due to factors other than design indexing.

Two possibilities are cited. The first is incorrect fabrication, e.g. the vendor trims the body panels too long, and the other is due to the as-is datum flow used in CC335. Evidence was presented earlier that supported the former notion of misfabrication. In the case of CC335 as-is indexing. the shop begins with the design process depicted above. They then "best fit" the body panels to minimize shimming at transverse floor beams and frame splices. Per local consensus they move body panels within a +/- 0.030 window. The as-is datum flow is shown in Figure 6.6.

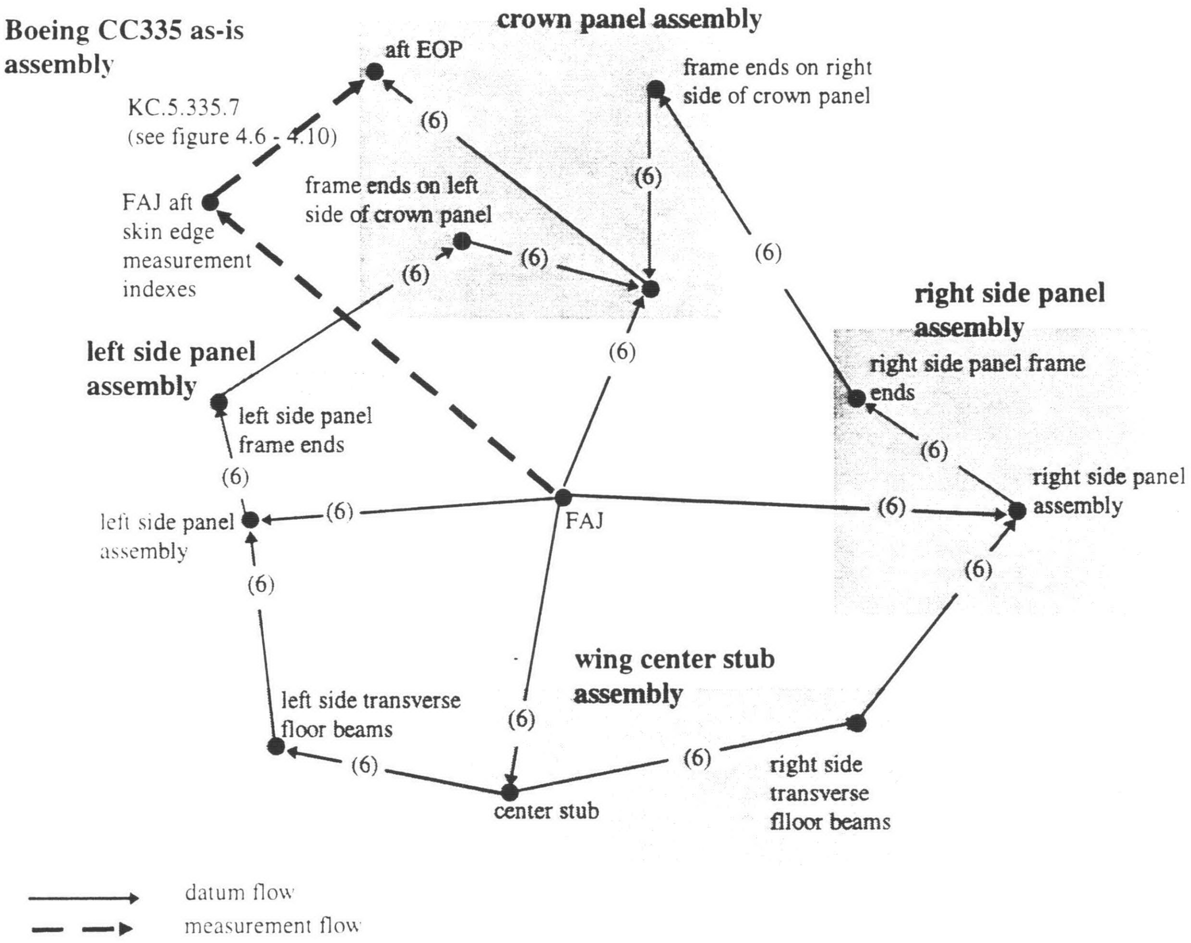


Figure 6.6 CC335 as-is datum flow for section 44 crown panel assembly

Note that in the as-is process the body panels are all over constrained. The left side panel, for example, is aligned to features on the FAJ and to center stub transverse floor beams and likewise for the right side panel. The crown panel, in turn, is aligned to frame ends on either side in addition to FAJ indexes. The obvious ramifications of such a scheme are that some of the indexes, namely the design features of the FAJ, will be violated. This also leads to a propensity for left/right assymetry due to matching floor beams and frames on either side. This condition is often observed in CC335 production: the left side panel is shifted forward up to 0.030 inches, the right side is at nominal, and the crown is twisted forward on the left side to accommodate the frame matching requirements.

6.1.2 Accumulated variation in datum flow: why CC335 must "best fit" in order to build

The DFC revealed consistent indexing for the as-designed process with respect to the aft skin edge but it is impossible for mechanics to build as designed because of tolerance requirements at other features: transverse floor beams and frames in this case. Maximum allowable floor beam station mismatch without an NCR is 0.063 and for frames the maximum is 0.056. Smaller mismatches are often observed and although they do not require an NCR to be written they are still a significant problem because of the shimming required.

The DFCs developed above can be used to demonstrate what the expected variation stack up at mating frame ends might be. The argument is based on the premise that the stringer clips, and not the Seaside FAJ, set the location of the frames. At Gifu (see Figure 6.2) stringer clips are located to stringers from the stringer forward EOP and stringers are located on skins by forward end coordination holes. The published accuracies for locating parts and holes in the sequence is:

Stringer coordination hole in skin panel	+/- 0.004
Forward coordination hole in stringer	+/-0.005
Location of clip along stringer	+/-0.005

The simple sum of the maximum deviations for a given clip is 0.014 so that clips on adjacent stringers of a given panel could be displaced by a maximum of 0.028 for station (assuming no other sources of variation existed). Now imagine that the two adjacent stringer clips nearest the frame end at the crown to side skin lap (stringer 14) are displaced this way. That is, at a given frame the clip on stringer 15 of the side panel is forward 0.014 and the clip on stringer 14 is aft 0.014. Now the frame end which extends halfway from stringer 14 to stringer 13 will be displaced 0.028 from nominal. This frame must be spliced to the adjacent frame on the crown panel which could be displaced by as much as 0.028 in the opposite direction. The deviation between the two frame ends would thus be 0.056.

This scenario is illustrated in Figure 6.7 which depicts a crown panel and left side panel skin lap and frame splice situation as it might appear in CC335. If the mechanics try to match the frame ends it will cause a large misfair at the forward and aft ends of the crown to side panel skin lap. If they attempt to index both panels at the forward EOP per design, the frame station mis-match will result in NCR activity. Because NCR activity causes production delays and rework the mechanics opt to violate the design indexing scheme.

Extending the scenario a bit farther, assume that the crown panel is already trimmed longer than nominal as data in Chapter 5 indicated is often the case. In figure 6.7 the crown must slide aft to match the frames. This aft movement adds to the excess length and compounds the problem in final body join due to the section 44 aft crown protrusion. Final body join is now faced with a dilemma similar to that which confronted CC335 because of the over-constrained nature of the assembly. As discussed in Chapter 5, final body join opts to lower the tail of the airplane to avoid NCR activity, production delays, and rework.

While the example is hypothetical it raises several questions:

- What does published accuracy for locating panel assembly parts mean and what are the distributions (e.g. 95% of holes are within +/- 0.04, uniform, normal)?
- Is the published accuracy best case optimism or realistic steady state manufacturing data based on actual process capability?
- What additional sources of variation exist that are not considered above (e.g. angular deflection of clip with published accuracy +/- 1°, straightness of frame, indexing, etc.)?
- What is the impact of feeding floor beam and frame station variation into airplane alignment?

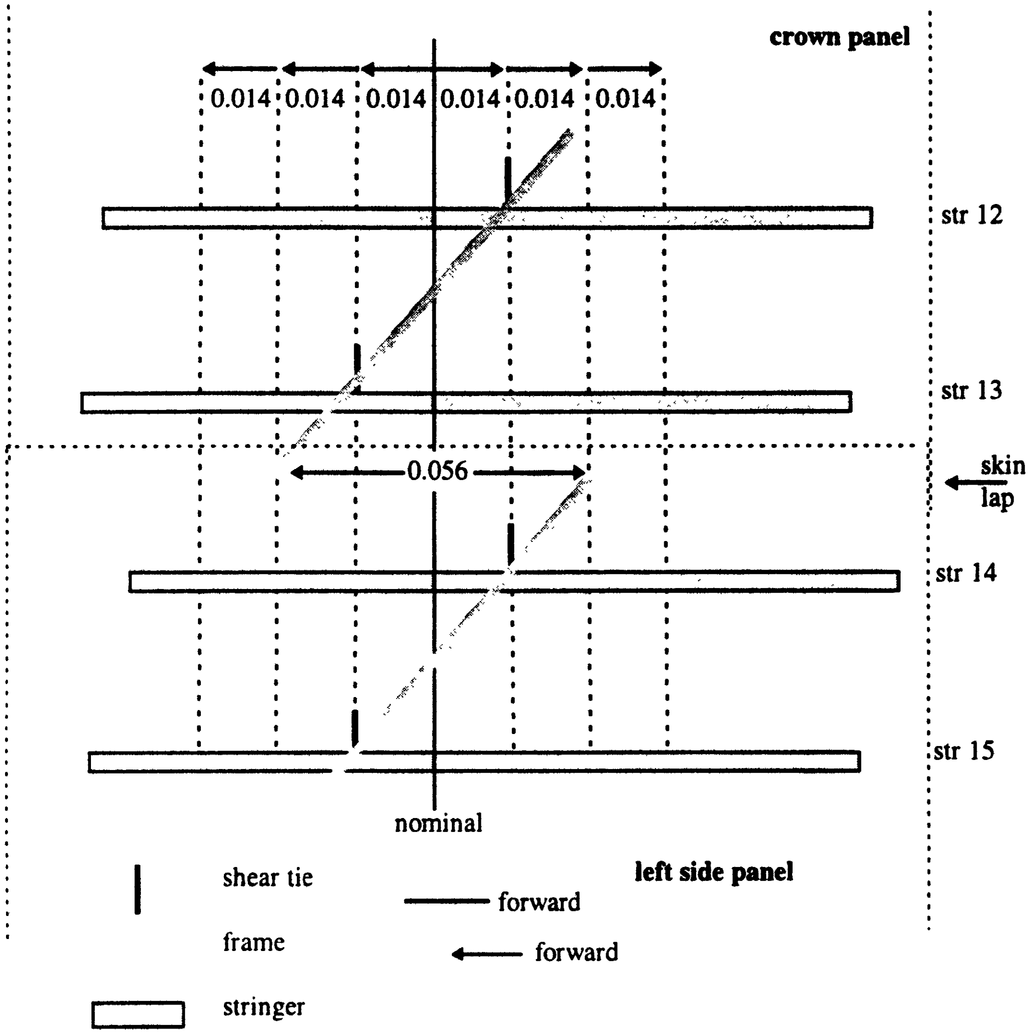


Figure 6.7 Accumulated variation effects in stringer clip placement on frame splices

6.1.2.1 Datum flow analysis in use at 777 manufacturing

Boeing 777 Process Engineers D. Watters and C. Schweigert have developed several superb illustrative tools that show qualitatively where variation enters the assembly process. One such figure is shown in Appendix 8. In order to arrive at the above conclusion that variation accumulates due to three datuming steps one simply adds the number of arrows needed to locate the feature of interest which, in this case, is stringer clips. Watters successfully applied this approach to problems in WBJ with good results.

Watter's independently developed DFC is similar to the DFC in use at MIT with the following main differences:

- Watters' approach is very easy to visualize and does not require much background knowledge to be readily comprehended. The fact that one may never have seen the assembly in question is not a hindrance because it is diagrammed in the datum flow.
- Watters' diagrams take more time to prepare because they are so graphic. As a result they also require more electronic capacity to manipulate and store.
- Watters' diagrams are good for one degree of freedom (STA, BL, or WL) whereas the MIT DFCs can be used for degrees of freedom from one to six (STA, BL, WL, and three rotational axes). As a result, the DFC used at MIT readily shows over-constrained assemblies (such as locating of frames in Figure 6.3 or the body panels in Figure 6.6).

7. Chapter 7 - Developments at Boeing since the internship

This chapter describes the vendor level process change that was implemented to correct the problem of section 44 body panel excess length and its attendant impact on aft join performance. The chapter begins by presenting a memorandum that was sent to KHI with details of the study performed in Everett. KHI's response and the results of the process change are then presented. Finally, follow up work by 777 Process Engineering is described. The group discovered a tooling measurement error in the CC335 FAJs. Their work explains the statistically significant difference between the measurements in the two FAJs that was described in section 5.1.3.1.

7.1 Change to the section 44 panel length trimming process

This section presents a memorandum that was sent to 777 factory management, Boeing International Business Operations, and KHI in order to correct the subject problem by requesting a change to the section 44 panel length trimming process. This is followed by a discussion of how KHI responded to the request and the effect that the KHI's process change had on Everett factory performance.

7.1.1 Memorandum to Boeing International Business Operations

U-30P0-WAM97-069

October 10, 1997

To:	C. Vinding	38-TA	Boeing International Business Operations
cc:	J. Chao	0W-JA	777 Factory Manager
	E. Chapin	0W-XK	777 Aft Body Structures Manager
	T. Copes	0W-XK	777 Body Structures Business Unit Manager
	H. Hajiri	03-KR	KHI
	W. McClenahan	03-KR	777 Process Engineering Manager
	T. Schulz	0W-CE	777 Final Body Join Process Center Manager
	C. Schweigert	0W-PL	777 Process Engineer
	A. Taniguchi	03-KR	KHI
	D. Watters	0W-PL	777 Process Engineer
	J. Westover	0W-PL	777 Process Engineer

Subject: Request for KHI to adjust section 44 body panel length trimming process.

Reference:
A) Engineering Drawing 101W5010
B) Engineering Drawing 144W0019
C) CC131 AFT JOIN KEY FEATURES QA Log
D) Key Characteristic KC.5.335.7UATL
E) Key Characteristic KC.5.KHI.7
F) Tool Drawing 144W0000 Sheet 902
G) Engineering Drawings 144W1010, 3010, and 4010

Background: Final Body Join (FBJ, CC131) has difficulty performing the aft join. Recurring issues are skin gap uniformity (Ref. A), skin and seat track station gap (Ref. B), and keel short edge margin. A salient indication is that the section 44 crown panel protrudes aft of the sides at stringer 14 by an average of 0.06[21,22]. When the condition is severe crown skin station gap reaches minimum allowable before other features are within tolerance[23]. This results in MRB activity with attendant production delays and cost ramifications.

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[21] All dimensions are inches unless otherwise stated.

[22] Ref. C; standard deviation 0.023; range of values 0.030-0.120.

[23] Reference C indicates that the aft join is significantly off center with crown skin gap averaging 0.055 close and LBL 11 seat track 0.049 wide of nominal. Left and right side panels average 0.014 and 0.010 closer than nominal and other seat tracks are wide per the LBL 11 signature (standard deviations around 0.027; a larger study gave a matching trend. The study makes no consideration of section 46 skin station, seat track positioning, or other factors that might cause this. As such, interpretation of these results as a measure of section 44 excess panel length implies the assumption that seat tracks and section 46 crown and side skins are close to nominal.).

Situation: The 777 Process Engineering Group conducted a study to determine the causes of section 44 crown to side panel misfairs[24]. The following conclusions were reached:

- individual crown panel lengths are fairly uniform from stringer to stringer.
- left and right side panel lengths are closely matched.
- crown and side panel lengths are statistically capable of meeting the final body join gap tolerance of +/- 0.080 although the process means are biased long.
- overall crown and side panel lengths consistently exceed engineering nominal.
- crown panel length exceeds side panel length.

A summary of the measurements considered is shown below. Positive numbers indicate long or aft deviation from nominal at the given stringer location and negative numbers indicate shortages from nominal.

Data Source	Left Side Panel (at stringer)	Crown Panel (at stringer)	Right Side Panel (at stringer)	Sample Group (L/N)	Comments
CC335 HVC (Ref. D)	0.063 @ 14L	0.090 @ 14L 0.071 @ 14R	0.047 @ 14R		Measures aft skin station deviation from nominal. Affected by multiple factors. See footnote 4.
CC335 Tool indexes (Ref F)	0.050 @ 19L	0.090 @ 1L	0.039 @ 19R		Absolute forward to aft panel excess length measured as offset from endgates (Ref. F)
CC335 Tool indexes (Ref. F)	0.030 @ 19L	0.082 @ 1L	0.037 @ 19R		Measures aft skin station deviation from nominal. See footnote 4.
Steel Tape at CC335 (approx. 75F)	0.02 @ 14L	0.07 @ 14L 0.07 @ 14R	0.020 @ 14R		End to end steel tape measurement from station 1035 to 1434 minus engineering nominal 398.830 per Ref. G.
FBJ QA (Ref C)	0.058 @ 19L	0.088 @ 1L	0.062 @ 19R		Measures difference between skin gap station deviation from nominal versus LBL 11 seat track station gap deviation from nominal. See note 2.
Steel Tape at KHI (Temp 85F)	0.040 @ 14L	0.067 @ 14L 0.057 @ 14R	0.05 @ 14R		Data provided by A. Taniguchi. End to end tape measurement minus nominal.
KHI HVC (Ref. E)	-0.006	0.002 @ 14L -0.003 @ 14R	0.010 @ 14R		KC data extracted from HVCS. Measures aft skin station deviation from nominal.

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[24] Everett assembly procedures contribute to section 44 panel station variability. The scope of this memo is restricted to section 44 panel length. Build procedures are addressed separately.

Proposal: The 777 Process Engineering Group requests that KHI adjust section 44 panel length trimming processes such that crown and side panel station lengths are centered around mean values 0.075 and 0.030 shorter, respectively, than their historical values.

Risk: Consideration was given to thermal expansion and contraction, seasonal variation in temperature difference between KHI and Everett, accuracy of measurements, assembly variation, sample size, correlation between data sets, difficulty of making process changes and impact on FBJ if skin gap is too wide. The requested adjustment is intended to keep long and short panels within engineering tolerance under likely temperature conditions (i.e. to keep the entire range of data within specification limits rather than to center the mean). A slightly larger and higher risk change would be required to center process means.

Analysis: A computer model was run using Ref. C and the proposed change from L/N 40-101. With no other changes three airplanes in the group of over sixty had skin gaps that went out of tolerance wide. In all three cases, however, sufficient margin existed on seat track gaps that the out of tolerance condition would never have occurred (the model had the artificial constraint of changing only skin gap). The change also caused 4 out of tolerance tight skin gap conditions and 13 wide seat track conditions to disappear and would have undoubtedly prevented numerous short edge margin problems due to the additional room for gap closure.

Deliverables: KHI should implement the proposed change to deliver section 44 crown panels that are 0.075 shorter and side panels that are 0.030 shorter than their respective historical means at the earliest possible date and inform Everett of which airplane number the change is made.

Summary: The CC131 aft join is significantly complicated by section 44 crown and side panels that are too long. Available data[25] support the proposed process change and risk considerations indicate minimal exposure. Elimination of all uncertainty is not possible and it is appropriate to consider the proposed change within the context of the alternative risk of doing nothing. Historical performance of the aft join (non uniform and tight skin gap, wide seat track gaps, short keel panel edge margins, trimming of panels in Everett, repetition of the September 1997 MRB in FBJ) suggests that the proposed change is a prudent course of action.

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[25] In contrast to the other data sources (which are supported by direct visual observation of the panels side by side in Everett and steel tape measurements at KHI) KC.5.KHI.7 shows crown and side panels to be within 0.010 of each other and tightly centered around nominal.

7.1.2 KHI response to change request

KHI maintained that the section 44 body panels were net trim and that the skin trimming process was centered on nominal. They defended their KC data in spite of overwhelming evidence that conflicted with it and challenged the integrity of the data collection process. Under pressure from Everett management following the September 1997 incident in final body join, KHI agreed to adjust the trimming process to remove an additional 0.075 inches from the crown panel and 0.030 inches from the side panels compared to the historical process means. This change was to have occurred after the third steel tape measurement was taken at KHI (i.e. on L/N 396 in October of 1997). Subsequently, however, KHI invoked numerous tactics to delay the change. On L/N 398 they began cutting crown panels 0.020 shorter and suggested that this should constitute completed action. Finally, the Body Structures Business Unit Manager initiated procedures to perform photogrammetric measurement of incoming section 44 body panels with the intention of rejecting any panels that did not measure within engineering tolerances. When news of this plan reached KHI they committed to implement the proposed change on L/N 406.

KHI implemented the process change by shifting their KC specification by the amount requested in the memorandum of Section 7.1.1. They maintained that their KC measurement system was accurate and that in their view they would actually be trimming the panels shorter than what was allowable per engineering. The new value for the side panel trimming process was agreed to be -0.030+/-0.040 and for the crown -0.075+/-0.040. This disturbed the author because the change was intended to adjust panel lengths relative to the historical process. Recent data trends (shown in Section 5.1.1, Table 5.1), however, indicated that KHI had been adjusting their measurement process over the past several months and that it was currently in close agreement with Everett measurements. If KHI adjusted the trimming process to produce short panels based on the measurement process that was now more accurate than in the past the panels would actually be too short.

KHI made process changes on several occasions without informing Boeing. They began trimming crown panels shorter by 0.020 inches on L/N 398 and did not notify Boeing of the change until afterward. On L/N 399 they trimmed all three body panels to nominal. When the airplane section was assembled in CC335 the author noted the condition (which was statistically out of control based on available process data) and sent a message to KHI to which they responded with an apology for not informing Boeing in advance.

In view of these events, it is conceivable that KHI discovered errors in their panel length measurement and trimming processes, corrected them, did not inform Boeing, and then went along with the changes that Boeing insisted they make. Under such a scenario there would be a risk of receiving panels that were now too short.

7.1.3 Results of the process change

The body panels for L/N 406 reached Everett several months after the internship ended. Figure 5.6 and Table 5.5 display the only data available to the author with which to evaluate the change. It is evident that the final body join skin gaps underwent a step change from being about 0.050 inches too small to values about 0.010 larger than nominal. These shifts are shown in Table 5.5 and are consistent with a change in section 44 crown panel length of -0.070 inches. Communication with Process Engineering and final body join personnel revealed that the process change may have overcorrected because after L/N 406 the skin gaps in final body join tended toward the wide end of the tolerance band and seat tracks closed to the small end of the allowable range. The short edge margin condition was said to have improved significantly for the ten airplanes after the change.

7.2 Tooling developments at Boeing since the internship

When the internship ended in December L/N 404 was in CC335 and L/N 394 was in final body join. Two Process Engineers were devoting considerable effort to model the aft join based on upstream measurements of section 44 and section 46 features at STA 1434. Laser trackers were used to measure skin edge and seat track locations. If their model indicated that interference would occur in the aft join (such as the September 1997 incident which cost the 777 factory an entire day of lost production) trimming was performed in advance of the body sections reaching final body join. It was expected that section 44 aft skin edge would center on nominal with the arrival of L/N 406 at which point KHI was to implement the change described in Section 7.1.

7.2.1 Laser Tracker Characterization of Panels and FAJ Majors[26]

To monitor the process change that KHI was to perform, overall crown panel lengths were measured starting on L/N 406 using Laser Tracker[27]. Measurement device accuracy and measurement point locations were based on KHI's measurement survey on L/N 406. A strong correlation was found between KHI's and Boeing's data both showing panels lengths an average of .080 inches short of nominal. FAJ measurement data, however, showed panel lengths near nominal begining at L/N 405.

Due to the difference between FAJ data and Laser Tracker data additional tool surveys were performed on the K.C. tool features (recall that a tooling survey on FAJ1 in October of 1997 revealed no out of tolerance conditions as mentioned in Section 5.1.3). Measurements were held relative to the primary seat track datums and results for units 1 and 2 are shown in Figure 7.1. Notice that on FAJ1 the skin panel STA index at STR 1.5L is located .020 inches aft and the measurement feature is located 0.013 forward. This would cause a panel measured in this tool to appear 0.033 longer than its actual length. Likewise, offsets were detected on unit 2. The FAJ out of tolerance conditions (e.g. features measured to be greater than 0.012 inches from their nominal position) have been corrected.

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[26] Work, text, and figures in this section are due to Boeing 777 Process Engineers C. Schweigert and D. Watters.

[27] The author is not familiar with the method used nor does he have sufficient information to estimate the measurement error.

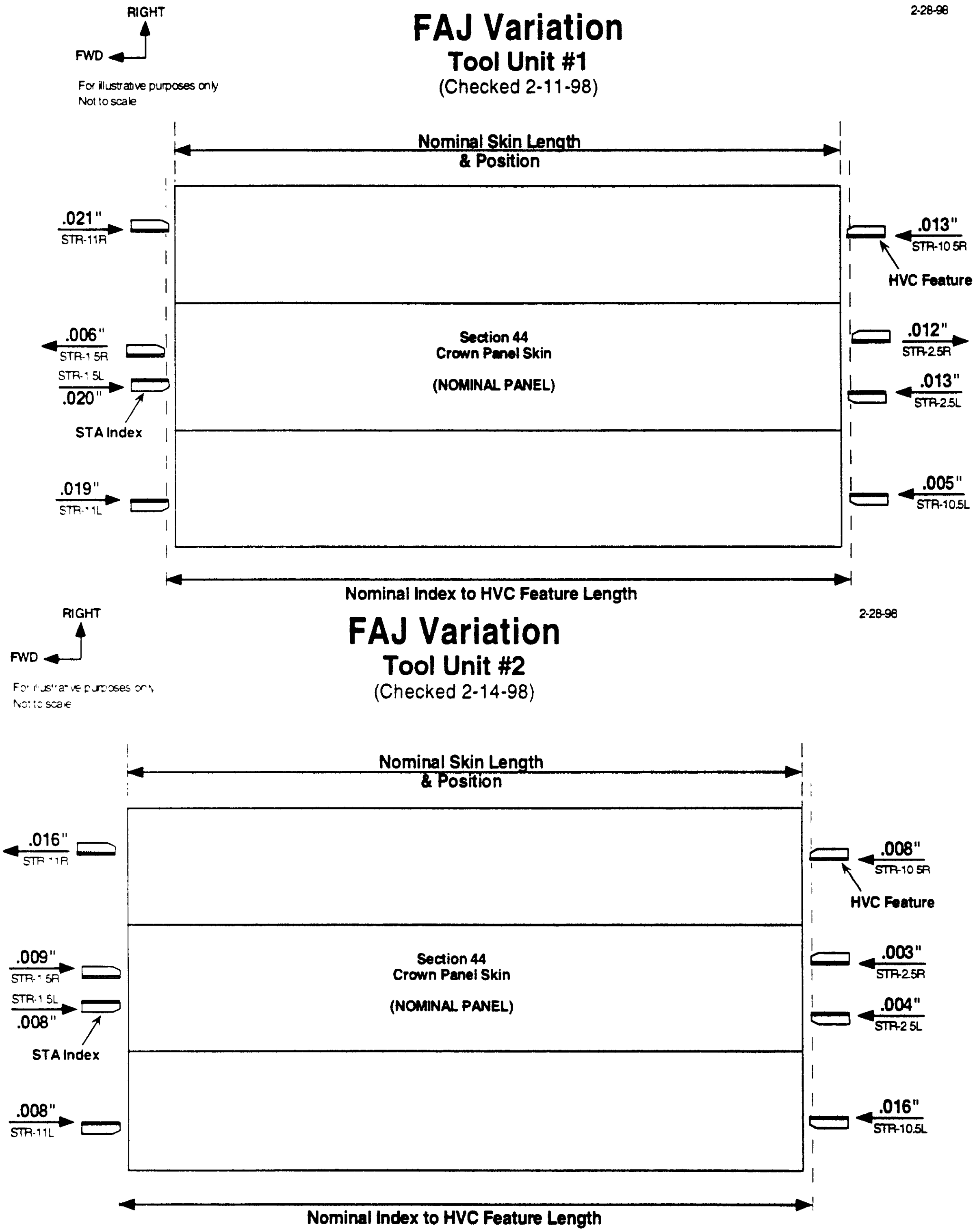

Figure 7.1 Laser Tracker Survey Results for FAJ 1 and FAJ 2

7.2.2 Effect of Laser Track results on baseline case study results

The offsets identified based on Laser Tracker are disturbing, particularly in view of the satisfactory tooling survey that was completed on FAJ1 in October, 1997. The question arises as to whether or not the findings refute the entire body of data presented in Chapter 5 or if the two can be reconciled.

Assume that the laser tracker has no error. It is highly unlikely that this is the case but this is a basic assumption that is taken for granted in the Boeing environment: measurement error is insignificant. The following corrections then apply (once again I thank C. Schweigert and D. Watters):

FAJ 1	fwd δ + aft δ = total δ (positive is toward panel/makes panel appear long)	
STR 19R	0.013 + -.002 = 0.011	(panels are 0.011 shorter than measured in FAJ)
STR 11R	0.021 + 0.013 = 0.034	(panels are 0.034 shorter than measured in FAJ)
STR 1.5R	-.006 + 0.012 = 0.006	(panels are 0.006 shorter than measured in FAJ)
STR 1.5L	0.020 + 0.013 = 0.033	(panels are 0.033 shorter than measured in FAJ)
STR 11L:	0.019 + 0.005 = 0.024	(panels are 0.024 shorter than measured in FAJ)
STR 19L	0.024 + -0.003 = 0.021	(panels are .021 shorter than measured in FAJ)

FAJ 2	fwd δ + aft δ = total δ (positive is toward panel/makes panel appear long)	
STR 19R	0.004 + 0.029 = 0.033	(panels are 0.033 shorter than measured in FAJ)
STR 11R	-.016 + 0.008 = -.008	(panels are 0.008 longer than measured in FAJ)
STR 1.5R	0.009 + 0.003 = 0.012	(panels are 0.012 shorter than measured in FAJ)
STR 1.5L	0.008 + 0.004 = 0.012	(panels are 0.012 shorter than measured in FAJ)
STR 11L:	0.008 + 0.016 = 0.024	(panels are 0.024 shorter than measured in FAJ)
STR 19L	0.004 + 0.008 = 0.012	(panels are 0.012 shorter than measured in FAJ)

Table 5.4 in Section 5.1.3 lists the measurements for the left, crown, and right side panels before the tooling error was detected. The results are repeated here for FAJ1 and FAJ2:

Panels as measured before tooling errors were detected (numbers represent inches longer than nominal as measured in the CC335 FAJ as discussed in Section 5.1.3):

	FAJ1	**FAJ2**
Left side panel at 19L:	0.055	0.037
Crown panel at 1L:	0.104	0.070
Right side panel at 19R:	0.026	0.054

Recall that in Section 5.1.3.1 it was shown that the differences in measurements between the two FAJs is statistically significant. Given the tooling feature offset information obtained by Schweigert and Watters (shown on the previous pages) the FAJ measurements can be corrected to reflect a more accurate estimate of panel excess length. The values shown below indicate the measurements in inches above nominal that would have been obtained in the internship study of Chapter 5 if the FAJ tooling features had been correct:

	FAJ1	**FAJ2**
Left side panel at 19L:	0.034	0.025
Crown panel at 1L:	0.071	0.058
Right side panel at 19R:	0.015	0.021

The agreement between the two FAJs is now very close. Invoking the assumption from Chapter 5 that the panels are from the same population the values from the two FAJs can be averaged. This results in the following process means (in inches longer than nominal):

Left side panel at 19L:	0.029
Crown panel at 1L:	0.065
Right side panel at 19R:	0.018

Had this information been available at the time that the change request was submitted to KHI in October of 1997 it is unlikely that 0.075 inches from the crown panel and 0.030 from each side would have been removed. Given these aggressive corrections one would expect the following process means after the change:

Left side panel at 19L: 0.029 - 0.030 = -0.001
Crown panel at 1L: 0.065 - 0.075 = -0.010
Right side panel at 19R: 0.018 - 0.030 = -0.012

The standard deviations from Table 5.4 can be used to show that post-change process should result in the following panel length distributions:

Left side panel at 19L: -0.001 +/- 0.025
Crown panel at 1L: -0.010 +/- 0.045
Right side panel at 19R: -0.012 +/- 0.034

Crown panels that are consistently 0.080 inches shorter than nominal can only mean that the trimming process was adjusted by more than 0.075 from the historical mean.

The author has an additional concern that measurement error in the Laser Tracker study is not available. This may not be an issue but a legitimate question is: how much would the calculated tooling offsets identified by Schweigert and Watters change if the laser equipment were removed, reinstalled, and the survey conducted again with a different set of qualified operators?

8. Chapter 8 - Conclusions and recommendations

The 777 is a monument to the ingenuity, creativity, and intellect of the people who designed and build it. From an organization standpoint, however, it might be argued that Boeing's intelligence is less than the sum of its parts. Cumulative genius, for which Boeing possesses the necessary ingredients, is absent. The 777 has experienced unexpected difficulties in production due in large part to hardware variability. Learning gleaned from the detailed study conducted during the internship sheds light on why this is so:

- inadequate consideration was given to production and measurement process capability and assembly integration risk during product and process design. This caused a production system that must inherently rely on inspection and rework in order to control variation within tolerance limits.

- corrective action procedures evolved reactively and are focused on events rather than being designed into the manufacturing system.

- incentives[28] along the customer-supplier channel are such that variation is washed into areas that are not inspected by QA and then knowingly passed downstream.

- the effect of accumulated variation culminates in final assembly where it can no longer be "washed out". At this point it takes tremendous effort to perform root cause corrective action because of poorly designed and inconsistent measurement systems, large time delays in information and material flows, and long distances from the original problem source.

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[28] KHI may have a bias toward trimming "long". The author found further statistical support for this hypothesis in a study conducted on the 767 forward join which indicated that 767 section 44 forward body panels may on average be longer than engineering nominal. Another study conducted by the 777 Process Engineering Group showed that 777 frame ends in body panels from KHI were subject to a "riding' condition due to excess frame length.

8.1 Conclusions

The highest leverage approach to dealing with variation is to design processes that minimize its magnitude and products so that variation is absorbed in areas where it is inconsequential. This is often referred to as robust design and results in a reduced need for corrective action. Proper design includes consistent measurement systems with known uncertainty so that root causes of problems are quickly pinpointed. Incentives should be aligned so that once the root cause is determined, everyone in the value chain works together to eradicate it. These pontifications, however, are of little help to 777 Division where the current level of hardware variation and the hard requirement to deliver airplanes on-time every-time require that symptomatic problem solving occur. This leaves line management with little time to conduct root cause investigations which, the case study demonstrated, take tremendous effort. For this reason, investment in groups such as the 777 Process Engineering team is vital.

HVC and Process Engineering are foreign to Boeing as it has approached manufacturing in the past yet they represent the right philosophy for how organizational learning and corrective action should proceed. HVC and Process Engineering are modeled on tested and proven manufacturing principles as described by Deming, Taguchi, the Toyota production system and others. A pervasive barrier to corrective action that the author noted was an imbedded linear mentality and a fixation on events rather than on systematic and statistical corrective action processes. Moreover, without better control over hardware variability, Boeing will not reap the intended benefit from efforts in the area of lean manufacturing. Finally, organizational learning can take place across product generations by impounding 777 HVC and Process Engineering data into the design of Boeing's next airplane. HVC and Process Engineering, despite having room for improvement, address all of these important issues.

8.2 Recommendations

Recommendations fall along four principle dimensions which overlap[29]:

- design considerations - integration risk and over-constraints, process capability, temperature standards, and designed corrective action structures.

- measurement systems and measurement error - measurements that check the intended KC, quantified measurement uncertainty, integration of HVC and QA where feasible.

- organizational culture and incentive systems - emphasize customer satisfaction, consider the effect of process improvements on the people who are being asked to produce them, encourage suppliers to deliver the nominal material condition.

- corrective action processes - get shops involved in tracking their processes, corporate level support for Process Engineering.

8.2.1 Design considerations

8.2.1.1 Identify integration risk[30] and avoid over-constrained assemblies

The chain metrics approach and/or the related DFC described by Cunningham and Whitney should be incorporated into the design stage to identify integration risk and over-constraints before production ramp-up begins. Regardless of requirements on paper, there are only six degrees of freedom in an assembly. This fact should be reflected as a planned constraint in the

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[29] For example, a key insight of the thesis is that the shop floor culture (of "best fitting" and the basic assumption that if QA buys the job it must be OK) is a rational response to an over-constrained assembly, lack of prioritization of KCs, and a management's emphasis on schedule.

[30] Integration risk is defined by Cunningham and Whitney as "the risk that apparently properly made elements will not function as desired when assembled or will require long error correction or adjustment. Integration risk rapidly spawns cost and schedule risk because integration problems are usually found late in product development and are hard to diagnose." See Bibliography.

design. Planning of build sequences to consistently deliver the DFC will free shops from the necessary "evil" of best fitting.

Once this is done there must be a prioritization or hierarchy of KCs such that the ones that are most important are delivered. For example, is it more important for final body join to satisfy QA requirements for skin and seat track station gaps or to align the airplane to make the laser alignment measurement read nominal (see measurement considerations in Section 8.2.2.1). Prevailing opinions in production are divided and which criterion is used often depends upon who happens to be at work the day the airplane is joined. The point is, operators may not know which effect is a 10^{-6} impact and which is 10^{-3}. Without a prioritization framework, however, the tradeoff decision will be made anecdotally and may vary from one mechanic or one shift to the next (as a further example see, Section 4.3.4 where two shifts in the same shop compete for the same six degrees of freedom).

8.2.1.2 Consider existing process capability in the design of engineering tolerances

There was inadequate consideration of production process variability in the design of 777 engineering tolerances. Support for this contention includes the ubiquitous +/-0.030 tolerance on almost every engineering drawing and the 7 lbs. EOEW NCR requirement (discussed in section 5.2.3) that affects fuel consumption by 0.0004%. Boeing's next airplane should draw on existing HVC, NCR, QA, or other manufacturing data and design engineering tolerances so that they can be achieved without rework. Designers should refrain from arbitrarily setting tolerances and ask:

- is the tolerance necessary to achieve design requirements?
- is the existing process or the expected process statistically capable of delivering the design tolerance?

For example, if final body join 777 QA data indicate that seat track station gaps have +/-3σ of 0.080 inches the design of the next airplane should allow that the tolerance be set accordingly or the processes by which seat track station gaps are delivered should be improved.

An example to further illustrate the point is described by Professor D. Whitney of MIT as follows: the length of the section 44 body panels considered in the case study is 398.830 inches with a tolerance of +/- 0.040 inches which is equivalent to 0.040/398.830 = 0.0001. Now imagine that it is desired to manufacture aluminum cubes with each side one inch long within a tolerance of +/- 0.0001 inches (analogous to the body panel tolerance limit). What type of process would be required to deliver such accuracy and precision? What type of temperature controls would be necessary? What kind of measurement systems and measurement uncertainty would be demanded? Are Boeing's processes consistent with what is required?

8.2.1.3 Consider temperature effects

The lack of a defensible temperature standard is potentially a large source of variation (see Section 4.3.2). Boeing should set a standard temperature at which the nominal dimension is to be achieved.

8.2.1.4 Plan for corrective action

Finally, plan for corrective action in the design of products and processes. Work by Cunningham shows that corrective action at Ford Motor Company, for example, works well because there is a design framework upon which it is based. Corrective action in final assembly will proceed more smoothly if mutually agreed upon measurement systems with common indexing and datuming and known uncertainty are in place before problems arise.

8.2.2 Measurement systems

8.2.2.1 Quantify measurement error

Measurement error should be measured and quantified in existing and new designs. Process capability studies for measurement systems is badly needed and measurements should be planned so that they check for the intended feature (see Section 4.3.4, Section 5.2.3, Section 7.2, etc.).

For example, using skin and seat track gaps as a proxy for airplane alignment is not a robust way to deliver straight airplanes because the body sections have accumulated variation. Work by 777

Process Engineering indicates that some body panels are trapezoidal which drives additional variation into airplane straightness if alignment is based on skin gap. Thus the laser alignment system is an excellent approach to achieve a top level airplane characteristic that represents a source of pride for many people in the 777 manufacturing program and a source of satisfaction to airline customers.

On the other hand, laser alignment data in Section 5.2.3 reveal a level of dispersion that should not be ignored. A measurement capability study is needed to better understand how much of this is due to alignment and how much is measurement noise. Moreover, the lack of certainty with measured values creates conflicting demands for assembly personnel and contentious debate that sometimes divides workers.

8.2.2.2 Integrate HVC and QA measurements where possible

Potential cost savings may accrue if Boeing can better integrate QA personnel and the measurements that they perform into the workshop environment. There seems to be considerable overlap between QA and HVC and eliminating or streamlining redundant measurements may be prudent. For example, it was shown in Section 5.2.2 that QA and HVC data for aft join skin gaps are identical. Using QA data in the HVC system may also improve the quality and status of HVC measurements (Sections 3.1.4 and 4.3.4.1 show why this is important).

8.2.2.3 Eliminate non-value added HVC measurements

Elimination of non-value added HVC measurements is being pursued with vigor by 777 Process Engineering. Section 4.3.4 and Chapter 5 present evidence that this work must continue if HVC is to succeed in confering economic benefit to the 777 program. Additionally, a credible HVC data base will be a powerful knowledge transfer vehicle for the next Boeing airplane program to build upon.

8.2.2.4 Use control charts (or some other method of assessing process performance) to reduce the number of measurements taken

Cunningham[31] describes how Ford Motor Company manages the need to obtain information amidst mountains of data. This is accomplished by reducing the number of measurements as soon as a process is demonstrated as capable.

8.2.3 Organizational culture and incentives

8.2.3.1 Make customer satisfaction a priority

This requires top management support but it will take more than words to drive the message home. Boeing is keenly aware of the importance of delighting its external customers. The company also has a military-like ability to align and mobilize its employees. Leaders should take advantage of these strengths to develop a clearer focus on the needs of internal customers.

8.2.3.2 Encourage vendors to deliver the nominal material condition

The thesis did not discuss the Taguchi loss function but there is abundant literature on the subject. A process that is off-center results in a loss even if the feature part is within tolerance. Vendors should be encouraged to set their processes to deliver the nominal material condition without "leaving a little extra on" just in case.

Vendors are afraid that if a part that is too small Boeing will have no alternative other than to reject it[32]. Moreover, Boeing demonstrates a willingness to trim parts when they are slightly oversized. This establishes an incentive for vendors to hedge against uncertainty by trimming long at a significant aggregate cost to Boeing. Until suppliers feel the pain that they are causing they have no reason to change.

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[31] Page 65 of Master's thesis, see bibliography.

[32] KHI stated plainly to the author during the case study that "it is better to be a little long than too short. You can always trim a little bit off but you can't put material back on".

Implicit within this recommendation is a link between *Lean* as embraced by Boeing and HVC/Process Engineering. *Lean* says never to knowingly ship an out of tolerance part; HVC/Process Engineering data provide the information and analysis necessary to fix the root cause so that the problem doesn't happen again.

8.2.3.3 Integrate HVC and "lean" activities

The lean initiative is often met with cynicism on the shop floor. One reason is that hardware variation is so large that it is difficult for workers to imagine continuous flow. From a mechanic's perspective, what difference does it make if you save two minutes per shift by kitting parts but then have to wait three days to get an NCR through the system?

Without better control over hardware variability, lean activities will not achieve the intended goals (also see Section 8.2.3.2).

8.2.4 Existing corrective action process

8.2.4.1 Strengthen feedback loops by involving shops in tracking their processes

Encourage workstations to get involved in corrective action. Shops should keep track of their processes and problems, do some control charting, and be able to answer simple questions such as:

- which airplanes had frame station mismatches, which frames were the mismatches on, and how much were they off by?
- which airplanes had a keel short edge margin?

It was nearly impossible for the author to get answers for even simple questions such as these during the internship using in place systems such as NCR records. This was true despite the existence of formal groups and information systems formally tasked to facilitate this type of feedback. The lack of viable feedback links to upstream build areas poses a formidable barrier to process improvement.

8.2.4.2 Support for groups that concentrate on root cause problem solving and help position the organization for knowledge transfer

In the current 777 manufacturing environment, management is appropriately committed and challenged to meet short-term delivery obligations. Consequently, operational management is extremely pragmatic and focused on immediate results. As the internship case study showed, however, root cause problem solving takes tremendous time and effort. This fact often places the short-term needs of the factory in conflict with the long-term needs of Boeing.

Only fundamental approaches to corrective action that address underlying causes will improve the current manufacturing situation because symptomatic approaches do not prevent problems from recurring. Moreover, to improve in the future, it is necessary to transfer the knowledge that resides within the production organization today into the design of tomorrow's airplanes.

HVC and Process Engineering programs at 777 represent a beginning step toward building the type of learning organization through which such goals can be accomplished.

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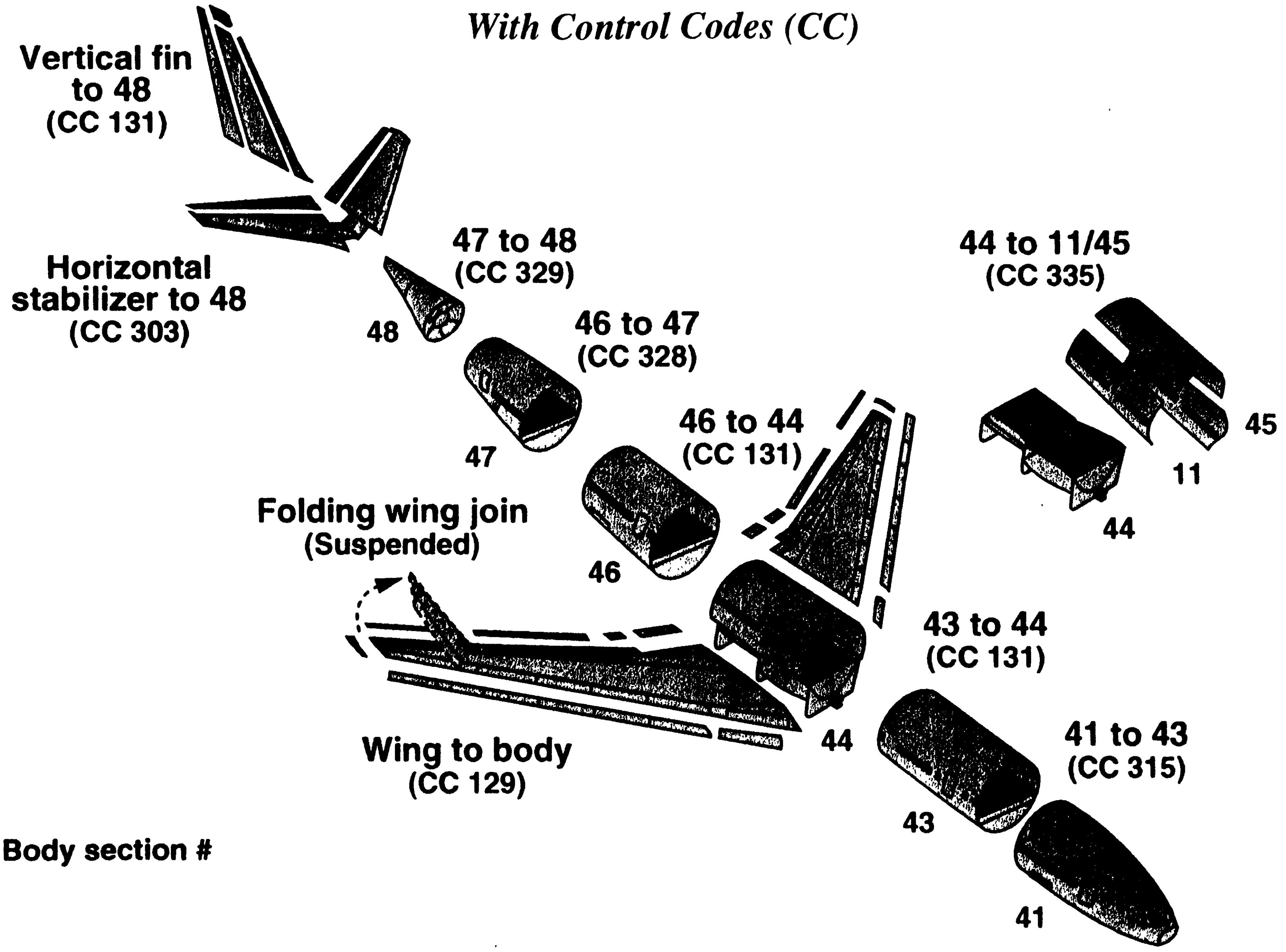
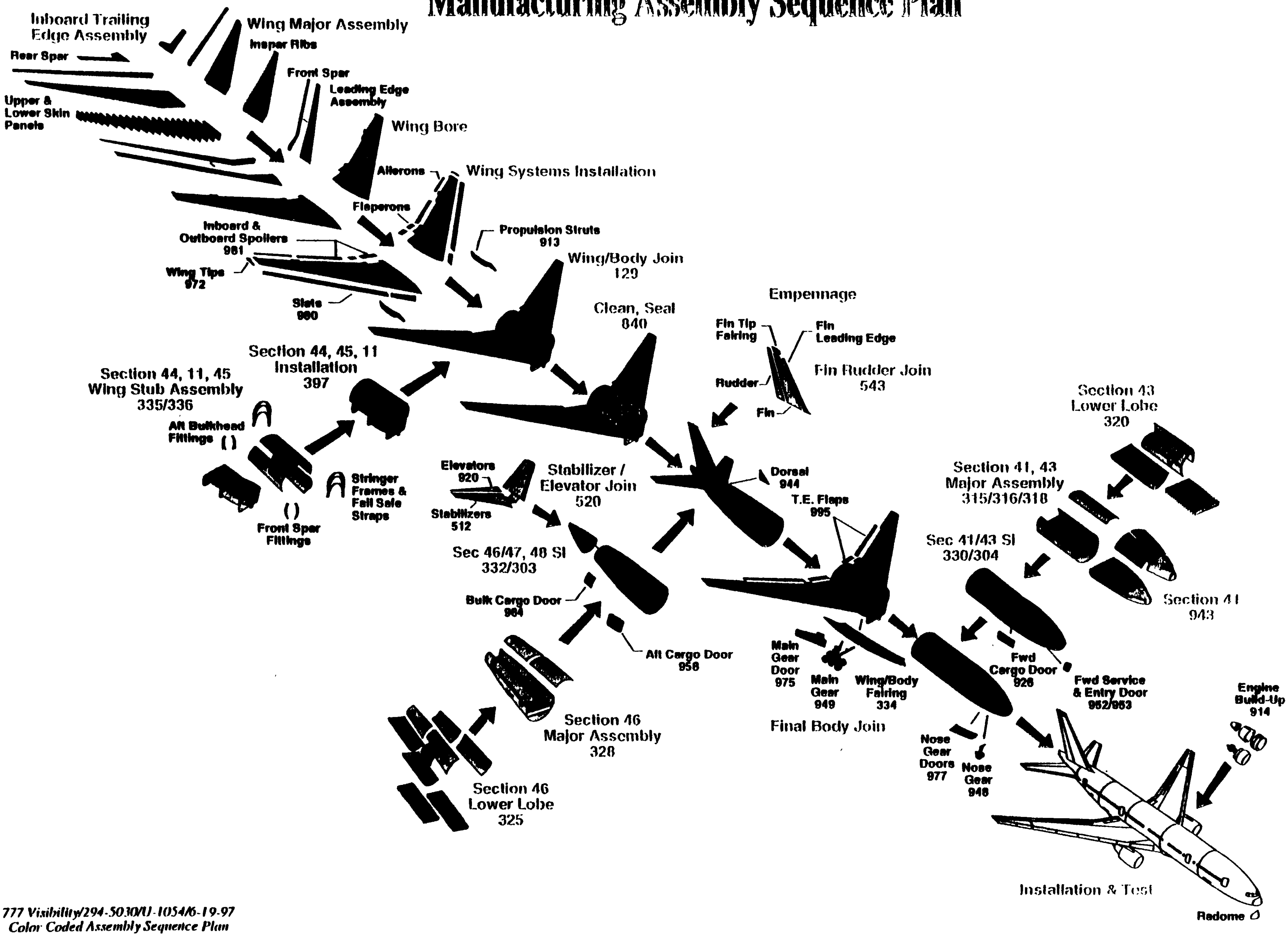
Appendix 1: 777
10 Major Body Joins

With Control Codes (CC)



777-6DS-109 R4 C
11-25-6-PW

Appendix 2: Model 777-200
Manufacturing Assembly Sequence Plan

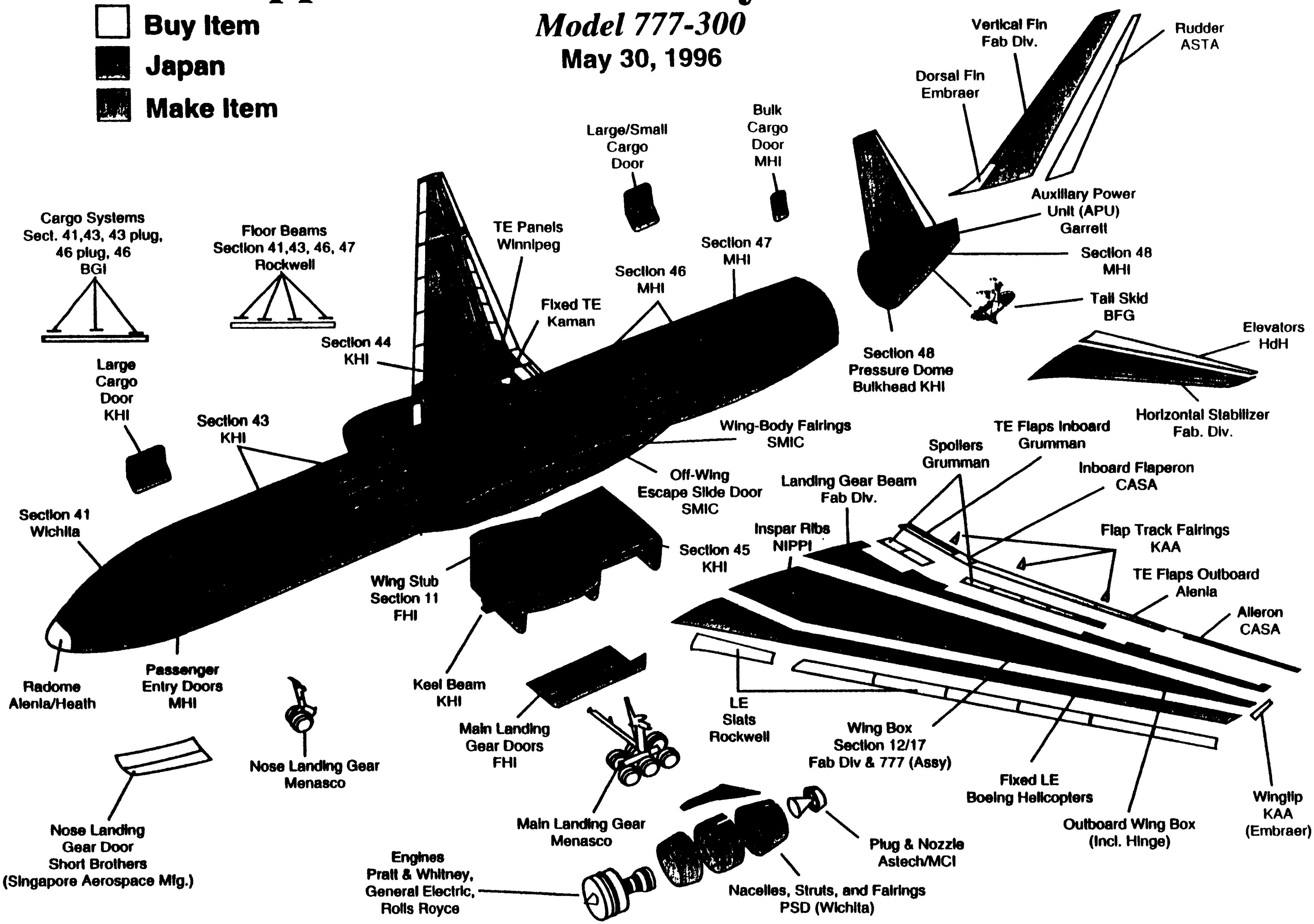


777 Visibility/294-5030/U-1054/6-19-97
Color Coded Assembly Sequence Plan

Appendix 3: Make/Buy

Model 777-300

May 30, 1996

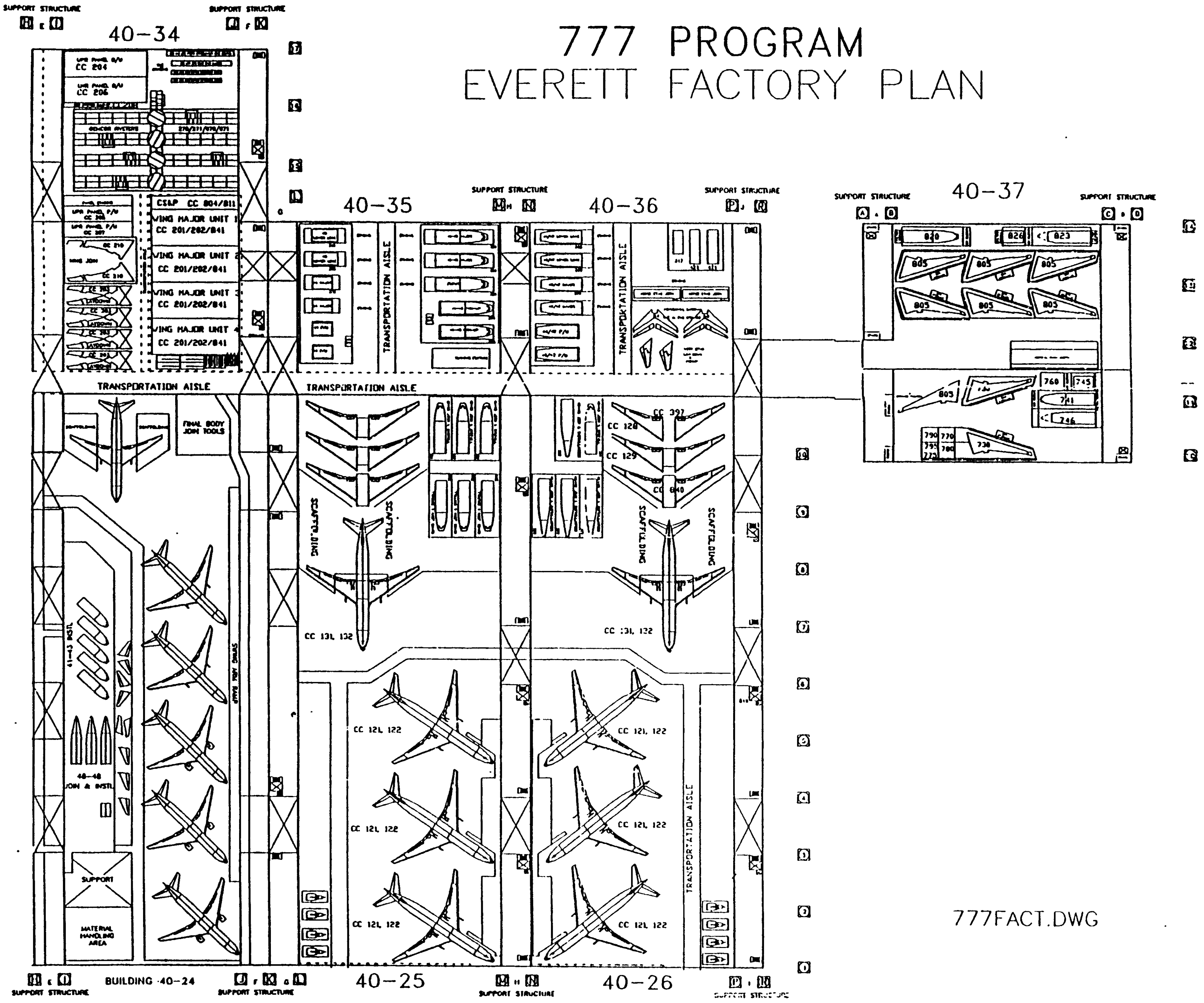


- PDT 777-300
  Gary Cloninger
  342-9695

777-6PM-202 C
6-5-6-whp

Appendix 4

777 PROGRAM
EVERETT FACTORY PLAN



777FACT.DWG

Appendix 5: Sample KHI KC data spreadsheet

GROUP_ID	PT_ID	MEAS	UPR_SPEC	LWR_SPEC	ENG_NOM	PHYS_PART	AP_NO	MEAS_DT	TIME	LOT_NO	SERIAL	TOOL	UNIT	SSN	ACTION	MISSING	VALID	CL_CALC	QUERY
KC 5 KHI 7	04A	0 248	0	0	0	930319001200	WA001	19-Mar-93	1200	930319001200		0					Y	Y	
KC 5 KHI 7	05A	0 25	0	0	0	930319001200	WA001	19-Mar-93	1200	930319001200		0					Y	Y	
KC 5 KHI 7	07A	0 26	0	0	0	930319001200	WA001	19-Mar-93	1200	930319001200		0					Y	Y	
KC 5 KHI 7	08A	0 26	0	0	0	930319001200	WA001	19-Mar-93	1200	930319001200		0					Y	Y	
KC 5 KHI 7	01A	0 244	0	0	0	930428000001	WA001	28-Apr-93	1	930428000001		0					Y	Y	
KC 5 KHI 7	02A	0 268	0	0	0	930428000001	WA001	28-Apr-93	1	930428000001		0					Y	Y	
KC 5 KHI 7	03A	0 248	0	0	0	930428000001	WA001	28-Apr-93	1	930428000001		0					Y	Y	
KC 5 KHI 7	09A	0.27	0	0	0	930428001200	WA001	28-Apr-93	1200	930428001200		0					Y	Y	
KC 5 KHI 7	10A	0 255	0	0	0	930428001200	WA001	28-Apr-93	1200	930428001200		0					Y	Y	
KC 5 KHI 7	11A	0.245	0	0	0	930428001200	WA001	28-Apr-93	1200	930428001200		0					Y	Y	
KC 5 KHI 7	04A	0.24	0	0	0	930706001200	WA002	06-Jul-93	1200	930706001200		0					Y	Y	
KC 5.KHI 7	05A	0.25	0	0	0	930706001200	WA002	06-Jul-93	1200	930706001200		0					Y	Y	
KC 5.KHI 7	07A	0 24	0	0	0	930706001200	WA002	06-Jul-93	1200	930706001200		0					Y	Y	
KC.5.KHI 7	08A	0.25	0	0	0	930706001200	WA002	06-Jul-93	1200	930706001200		0					Y	Y	
KC 5 KHI 7	01A	0.25	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC.5 KHI.7	02A	0 25	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC.5 KHI 7	03A	0.25	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC 5.KHI.7	09A	0.24	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC 5 KHI 7	10A	0.23	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC 5.KHI 7	11A	0.22	0	0	0	930729001200	WA002	29-Jul-93	1200	930729001200		0					Y	Y	
KC.5 KHI.7	04A	0.263	0	0	0	930823001200	WA003	23-Aug-93	1200	930823001200		0					Y	Y	
KC.5.KHI.7	05A	0.248	0	0	0	930823001200	WA003	23-Aug-93	1200	930823001200		0					Y	Y	
KC 5 KHI.7	07A	0.247	0	0	0	930823001200	WA003	23-Aug-93	1200	930823001200		0					Y	Y	
KC 5.KHI.7	08A	0.256	0	0	0	930823001200	WA003	23-Aug-93	1200	930823001200		0					Y	Y	
KC 5 KHI.7	01A	0.25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	
KC.5 KHI.7	02A	0.25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	
KC 5.KHI.7	03A	0.25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	
KC 5.KHI.7	09A	0 25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	
KC 5 KHI 7	10A	0.25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	
KC.5.KHI.7	11A	0 25	0	0	0	930830001200	WA003	30-Aug-93	1200	930830001200		0					Y	Y	

Key to Point ID:	Panel	Left Side Panel	Crown Panel	Right Side Panel
	Point ID	01A, 02A, 03A	04A, 05A, 07A, 08A	09A, 10A, 11A
	Stringer	28L, 24L, 14L	14L, 1L, 1R, 14R	14R, 24R, 28R

Appendix 6: Definitions

Back-shop - a build position or control code located upstream in the factory. This is a relative term casually used to refer to any of a number of upstream suppliers.

Best fitting - process by which production workers attempt to satisfy mutually exclusive requirements in an over-constrained assembly. This occurs because building the part according to the design build plan will cause features at other critical interfaces to fall outside of their allowable tolerance limits resulting in production delays and rework. If it is possible to avoid these problems with small undocumented departures from the design build plan and bring the nonconformance condition within tolerance workers often take it upon themselves to do so. These effects are caused by variation in the manufacturing processes.

BL - buttock line. Line parallel to the center line of the airplane fuselage. Measured in inches from the center of the aircraft outboard to the left or right as viewed from the rear of the airplane.

CC - control code. Build position, shop, or workstation that is tasked with producing a subassembly, assembly, or installation in its deliverable condition.

CC131 - Final body join or FBJ. Work station responsible for joining the forward and aft bodies of the airplane to the wing center section.

CC335 - section 44 build shop. Responsible for assembling the wing center stub from the component assemblies as shown in figure 3.2.

Corrective action - formal process by which any condition that could affect airplane safety, service life, operating costs, or maintainability are resolved before the airplane is delivered. Anything requiring corrective action is reviewed by QA, Engineering, and Manufacturing to ensure that the product is not compromised with respect to these requirements.

Datum - plane or axis that is assumed to be exact for purposes of measurement. Most geometric features are measured relative to datum features.

Effectivity - number assigned to an airplane in production to identify basic engineering configuration. Effectivity numbers are unique to a particular airplane and are of the form WA001, WB076, WY997, etc.

EOEW - equivalent operating empty weight. The weight in pounds that would have to be added to an airplane to cause an equivalent fuel burn effect as some other change that cannot be directly measured in weight. For example, a mispositioned exterior surface may cause a drag penalty resulting in increased fuel burn which can be converted to an EOEW and then compared or ranked against something else. Boeing considers EOEW less than 7 lbs. to be insignificant. The 757 aerodynamic study in Section 5.2.3 indicates that a 1 pound increase in EOEW results in an additional fuel burn of 15.7 gallons per year.

EOP - end of panel

FHI - Fuji Heavy Industries. Japanese industrial partner to Boeing responsible for assembling the section 44 center stub (section 11/45) and supplying other parts.

FAJ - floor assembly jig. Large stationary tool used to hold and locate parts during assembly

flowdown - process in which key elements (i.e., engineering datums, key characteristics, and part-to-tool or part-to-part indexes) are tiered down through the drawing and build trees in a structured relationship to ensure continuity from installation to the detail level.

Greenline - form used to carry authorization for rework required by an NCR to other airplanes when a recurring condition exists.

HVC - hardware variability control. Cross functional management of design and build processes that impact the fit, performance, and service life of airplane hardware.

Integration Risk - the risk that apparently properly made elements will not function as desired when assembled or will require long error correction or adjustment. Integration risk rapidly spawns cost and schedule risk because integration problems are usually found late in product development and are hard to diagnose.

KC - key characteristic. Attributes or features (dimensions, specifications) of a material, part, assembly, installation, or system in which variation from nominal has the most adverse effect upon fit, performance, or service life.

KC.5.KHI.7 - KC measurement performed in the KHI Seaside plant FAJ to determine the aft skin edge station location of section 44 body panels.

KC.5.335.7 - KC measurement performed in the CC335 FAJs to determine the aft skin edge station location of section 44 body panels.

KHI - Kawasaki Heavy Industries. Japanese industrial partner to Boeing responsible for supplying section 44 body panels and other parts.

LBL11 - left buttock line 11.00. The reference buttock line corresponding to the LBL 11 seat track that serves as the BL datum for the 777. LBL11 was selected as the BL datum because it coincided with a hardware feature to which airplane parts could be indexed during the build process.

Line Number - unique number assigned to an airplane to identify its relative position within the planned airplane delivery order.

L/N - line number.

Misfair - Condition due to hardware variation in which two panel edges that are designed to be flush are slightly displaced relative to each other. An overhead diagram of such a condition is shown in Figure 5.1.

MHI - Mitsubishi Heavy Industries. Japanese industrial partner to Boeing responsible for supplying section 46 body panels and other parts.

MRB - material review board. Representatives from Engineering and QA who determine how nonconformance conditions will be dispositioned (i.e. what will be done to correct the nonconformance).

NCR - nonconformance reject also referred to as nonconformance reject tag or simply tag. Documentation providing traceability for a part, system, or process that does not comply with current specifications.

O&IR - operating and inspection requirement. A job in the production phase of an assembly that must be documented and completed before the build cycle can considered finished.

Over-constrained assembly - assembly step that attempts to control more attributes than what is physically possible. Over-constrained conditions arise because the location of a given feature on a rigid structure cannot be independently changed without changing the location of other features on the same part. Only a perfect part in a perfect assembly will have all features match exactly.

QA - quality assurance.

RAJ - rivet assembly jig. Tooling fixture used to hold and locate parts during assembly operations.

SME - shipping mechanical equipment. Large metal shipping fixture used to contain airplane assemblies during transport.

Station - identifies one or a range of edge views of vertical reference planes that divide the airplane into transverse sections. Station is measured in inches from the nose of the airplane aft.

STA - station.

Waterline - line parallel to the horizontal reference line of the airplane used to reference vertical locations. The waterline reference begins at ground level and is measured in inches in the upward direction.

WL - waterline.

WL200 - Waterline 200.00. The waterline datum for the 777 corresponding to the top surface of the LBL11 seat track. WL200 was selected as the WL datum because it coincided with a hardware feature from which the airplane parts can also be indexed.

Appendix 7: Tutorial on datum flow chain

Datum flow chains

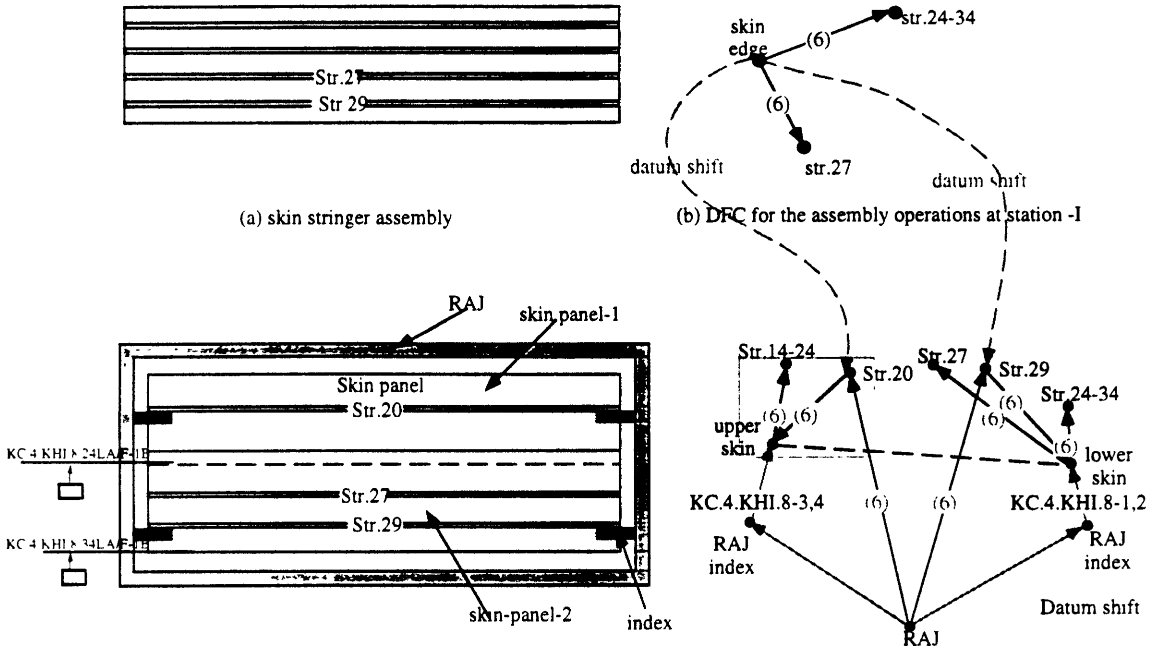
A datum flow chain is a directed acyclic graphical (a graph with no loops or cycles) representation of an assembly with nodes representing the parts and arcs representing dimensional relationship between them. (See Fig. 1) Every node represents a part or a fixture and every arc transfers dimensional constraint from the part at the tail to that at the head. The number shown on the arc indicates the number of degrees of freedom constrained by the arc. A typical part is joined with several parts in an assembly. However every joint does not transfer dimensional constraint and determine the location of the part. Some joints are redundant and are there to provide strength or support (called "contacts"). The joints that define dimensional relationships between parts are called "mates". If these distinctions can be expressed carefully and mathematically, then we can construct directed graph representations for dimensional transfer in a declarative way, providing a basis for synthesizing tolerance achievement rather than doing tolerance analysis on sets of geometric decisions whose underlying logic we have no way to represent. We call this directed graph of "*mates*" the *datum flow chain* that assigns a hierarchy to the joints between parts by defining which part(s) locates which other part(s) in the assembly. Contacts are shown here as dashed lines only for the sake of clarity. Loops or cycles in a DFC would mean that a part locates itself once the entire cycle is traversed, and hence are not permitted in a DFC.

A DFC is constructed for each assembly station. The red dashed curved lines show the transfer of index points (datum shifts) across assembly stations. During assembly operations, mates are directly associated with the delivery of KCs. Hence a DFC can be used to track the delivery of KCs in an assembly process.

A typical DFC has only one node that has no arcs directed towards it, which would represent the part from which the assembly process would begin. This is similar in logic to the base part. Every arc constrains certain degrees of freedom depending upon the type of mating conditions it represents. The sum of the degrees of freedom constrained by all the incoming arcs to a node should be equal to six unless there are some kinematic properties in the assembly or designed mating conditions such as slip joints which can accommodate some amount of pre-determined motion. A sum greater that six would mean that the part is over-constrained. Pre-stressing or other finessing of an over-constrained part may be required in order to complete assembly.

The construction of a DFC is explained using the following example:

In Fig. 1, the example of a side skin panel of a 43 section is used to illustrate the construction and interpretation of a DFC. In Fig. 1(a) is shown a typical skin stringer assembly. The skin has pre-drilled holes which are used to match assemble the stringers. The lower edge of the skin was used as a primary reference datum when the holes on the skin were drilled and as a primary locating index when the stringers are assembled to the skin. This information is represented using a DFC in Fig.1(b). The skin is represented as a node and has arrows directed towards nodes representing stringers. This means that the location of all the stringers in the resulting assembly is determined by the datums on the skin. A separate node is used to represent Str. 27 just to differentiate it from the rest of the stringers.



(a) skin stringer assembly

(b) DFC for the assembly operations at station -I

(c) assembly of the skin panels

(d) DFC for the assembly operations at station -II

[illegible] shown inside a shaded region
[illegible] and hence are fully
[illegible] respect to each other

Fig. 1: Example construction of a DFC -- (a) a typical skin stringer assembly, part of a side skin panel of a 43 section -- (b) the DFC for the assembly in (a) -- (c) assembly process of the two panels constituting a 43 section side skin panel -- (d) the DFC for the assembly process shown in (c).

The next stage of the assembly process is the assembly of the two skin panels to form the side skin super panel, on a fixture (called RAJ at KHI), as shown in Fig. 1(c) . The two skin panels are indexed off the RAJ by using Str.20 on the upper panel and Str.29 on the lower panel as locating indexes during assembly. Once the RAJ has located the two skin panels, they are fastened together to form a lap joint. This process is represented using the DFC shown in Fig. 1(d). In addition to the datum flow, the measurement process is also represented by supplementing the DFC with measurement flow information (shown in purple).

The DFC can also capture and represent the shift of datums and indexes from one assembly station to another, if they occur during assembly. The red dashed curved lines (Fig. 1) show the transfer of index points across assembly stations. The existence of such datum shifts mean that the accuracy of the resulting assembly at any assembly station is not just a function of the operations performed at that station but also on the assembly operations performed at prior assembly stations. For example, in the example illustrated in Fig. 1, the accuracy of the resulting super skin panel assembly depends on the accuracy of the location of Str.20 and Str.29 with respect to the skin edge at assembly station-I. The DFC captures this information explicitly and enables the designer to determine which assembly operations done at prior assembly stations need to be monitored.

Another important consequence is the ability to derive the tolerance chain for any KC from the DFC. Most often current CAD systems represent only the final configuration of the assembly and hence tolerance analysis is performed only on the final configuration of the assembly. However to perform a meaningful analysis, all the intermediate stages of the assembly process should also be considered and all the fixtures used during the intermediate stages of the assembly process should an integral part of the analysis. The DFC naturally leads to the construction of the tolerance chains that includes all the contributors to dimensional variation. A tolerance chain between any two parts A and B is a path of solid lines traced out from the node representing part A to the node representing part B in the DFC.

What follows from the above discussions is a very interesting observation that the DFC passes through the supply chain for the assembly. A tolerance chain between two parts in the same subassembly can cross organizational barriers, depending upon the choice of location and indexing methods employed. To perform any kind of meaningful tolerance analysis, knowledge of the assembly procedures at supplier sites is very essential to determine all the variation contributing elements. Using the DFC, all the contributing elements to any tolerance chain can be correctly determined.

This is illustrated by the following example. Say we wish to determine the position and orientation of the edge of the lower skin relative to the breakrings on the side skin panel at CC 320 (Boeing). The resulting tolerance chain is shown in Fig. 2. Thus, the tolerance chain between two parts in the side skin subassembly at Boeing passes through fixtures at KHI and back to Boeing.

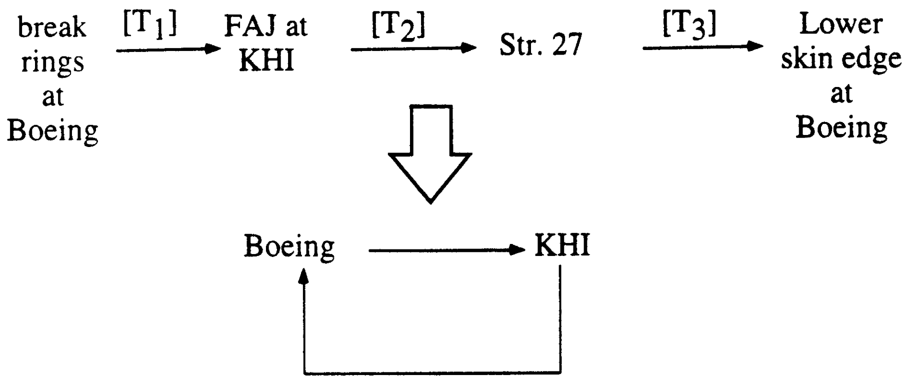


Fig. 2: Tolerance chain derivation from a DFC

Each directed arrow in a DFC can be represented mathematically using 4x4 coordinate transformation matrices. $[T_i]$ is a 4x4 transformation matrix from the coordinate frame on the part at the tail of the arc to the coordinate frame on the part on the head of the arc, as shown in Fig. 4. $[T_i]$ includes the effect of the variations involved in these coordinate frames. With this tool the designer is now able to include completely all the contributors to the tolerance chain and model what really is happening during assembly.

The procedure employed to arrive at this result is explained as follows. This example builds on the example in Fig. 1 and looks at the next stage of the assembly process (the step after Fig. 1(d)) where the frames and the breakrings are assembled to the skin panel. This stage is shown in Fig. 3.

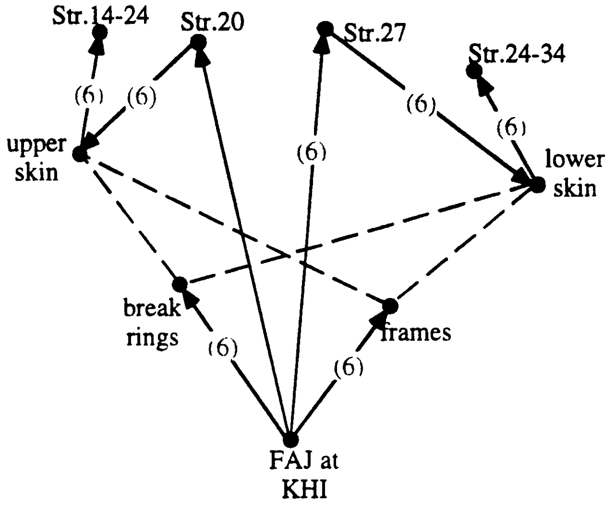


Fig. 3: The DFC for the assembly operations in which the frames and breakrings are added.

At final assembly (Boeing) the above assembly is indexed using the breakrings on a fixture (FAJ at CC 320). This is shown in Fig. 3.

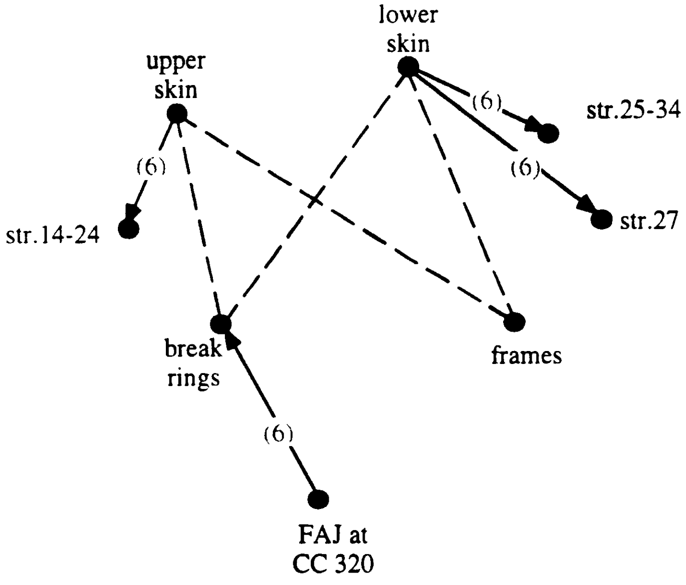
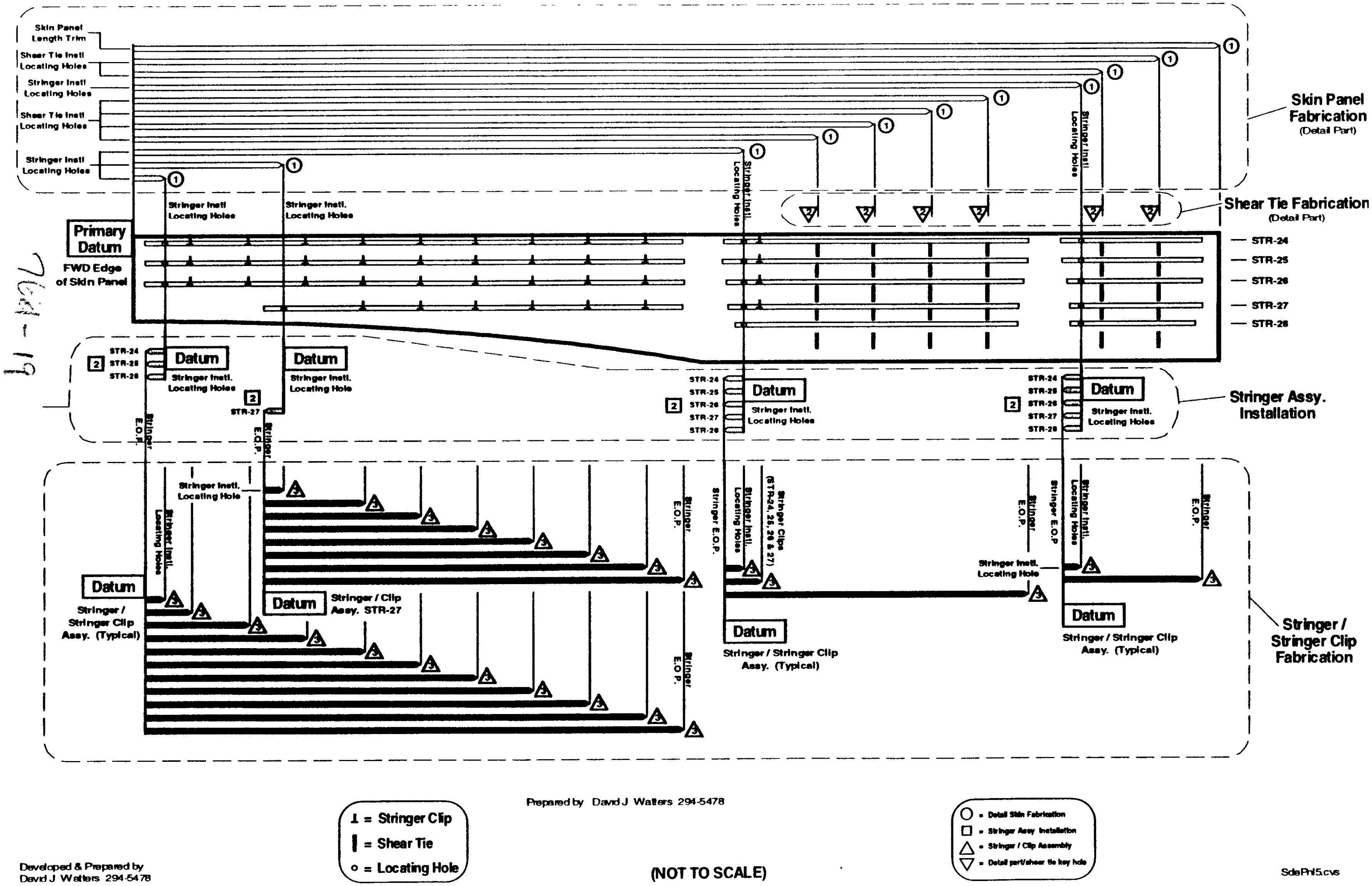


Fig. 4: DFC for final stage assembly of the side skin panel at CC 320

To determine the position and orientation the edge of the lower skin relative to the breakrings, all that needs to be done is to trace the DFC (solid lines) from the breakrings to lower skin edge and the path constitutes the tolerance chain. There is no direct path in Fig. 3, of solid lines -- which carry dimensional constraint -- between the breakrings and the lower skin. This means that the path from the breakrings to the lower skin passes through a set of fixtures and parts at an earlier assembly operation. The path starts from the breakrings (Fig. 3), passes through the FAJ at KHI (Fig. 3), Str. 27 and finally to the lower skin (Fig. 3). The resulting tolerance chain is shown in Fig. 2. Any kind of tolerance analysis that ignores the effects of the FAJ at KHI in the tolerance analysis will not yield accurate results.

Appendix 8: Watters' manufacturing datuming for section 44 side panel



764-19