ANALYSIS OF CUSTOMER-DRIVEN AND SYSTEMIC VARIATION IN THE AIRPLANE ASSEMBLY PROCESS

by

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Abstract

The Boeing Company has long been troubled by the unpredictable nature of the costs of the manufacturing and assembly of an airplane. Due to the complexity of the product it has been exceedingly difficult to determine whether the process is inherently unstable or if there are unique characteristics of individual planes that drive the differences in cost.

This paper investigates the drivers of the variation of cost in the airplane assembly process. Using the 777 as a case study, we evaluated over two hundred consecutively built aircraft to gain an understanding of those factors that contribute to the overall cost of assembly of each plane.

Our conclusion was that there is, in fact, considerable stability to the airplane manufacturing process. While Boeing must continue to deal with the inevitability of unforeseen events, there is considerable evidence to support a high predictability of the costs of each airplane based on factors that are known at the time the order for the plane is placed and long before the plane is manufactured.

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Foreword

LFM and the Internship

The Leaders for Manufacturing Program (LFM) is a joint program between the MIT Sloan School of Management, six MIT engineering departments, and over two dozen sponsoring manufacturing companies. The program's mission is to help strengthen manufacturing around the world by developing its students to be future leaders, increasing the body of applied theory and research on manufacturing, and enabling the practical application of the theory and research to the participating companies. Approximately fifty students in each class spend two years in the program. Most of the two years the LFM students spend taking classes towards dual Masters degrees in management and engineering. However, the first half of the second year the students disperse to the sponsoring companies for a six-month internship. Internships are an integral part of the LFM Program. Not only do the internships give the LFM students an opportunity to apply their academic learning, but also they give the companies access to MIT research and the latest applications of theory and knowledge through the students and their faculty advisors. Each internship project culminates in a student thesis that helps satisfy the requirements of the MIT degrees.

Project Charter

This project originated with several of the members of the Boeing 777 operations leadership team. Boeing had long been experiencing problems with variation in the final assembly of the airplanes. While their collective intuition suspected the causes, they were looking for confirmation that the variation indeed was a problem, an in depth study of the principle factors causing the variation, and suggestions on how to address the problems. This project was borne on the notion that there is something inherently different in the configurations of the planes (predominantly the multiple options and configurations) that is driving dramatic differences in the labor units it takes to build each plane. Furthermore, they suspect that some prior knowledge of these options and configurations and other characteristics of the plane may in fact lend itself to enhance Boeing's overall ability to predict this variation. Thus, it was proposed that extensive interviews be conducted with the multiple divisions responsible for designing, building, selling, and delivering the 777-model airplanes and the resulting data collection and analysis be carried out. While the projects focus was limited to the 777 it is widely believed that any conclusions would likely be applicable to other Boeing models as well, particularly the twin-aisle aircraft (the 767 and the 747). In fact, the 777-model incorporated many of the latest design and manufacturing techniques to minimize variation and facilitate production, such that the other older models would be experiencing exaggerated circumstances and would benefit even more from any conclusions drawn.

Unlike many LFM internships that tend to stray from the original project proposal, this project stayed remarkably in line with its original charter much to the credit of the Boeing 777 operations leadership team. I firmly believe that the 777 program is competently marching forward and setting an example for all of Boeing to follow. I only hope that our conclusions here contribute to their inevitable successes.

Acknowledgments

I personally want to thank everyone at Boeing for an incredible six months. My experience there was immensely rewarding both personally and professionally. Particularly, I want to thank Glen Evans, Tim Copes, and Jackson Chao not only for sponsoring my project, but also for giving up their valuable time and offering their mentorship. Thanks also to all the LFM alumni for being so welcoming, especially Keith Jackson, Charlie Hix, and Steve Llorente. I am indebted to Mike Wargel, Kathy Reid, Matt Madeksza, Bob Taylor, and Lisa Buck for the efforts in helping me to learn about Boeing, to meet the right people, and to find the material I needed. Thanks to Ken, Glen, Pete, Mike K., Michael F., Mike B., Diane, Pat, and Greg for putting up with me daily—it was great to meet all of you. And, of course, thanks to Matt Napier for keeping me focused on the important things.

Beyond Boeing I want to thank my advisors: Duncan Simester, Kevin Otto, and Al Drake. I have learned a tremendous amount and I hope we stay in touch. Thanks also to Don, Nancy, and the rest of the LFM program office for your support during the internship. Meghan, Chris, Tim, Erik, and Carl—you guys are awesome. Thanks for everything. Finally, thanks to Chester and Kate, my parents, Cara, Lizza, and Betsy. I have greatly appreciated your support for these entire two years.

Oliver Meschan Weir
May 19, 2000

Chapter 1: Background

1.1 The Boeing Company

Ever since its founding by William Boeing on July 15, 1916, The Boeing Company has been a dominant presence in the aerospace industry. From a tiny twin-float seaplane in 1915 to the B-17 "Flying Fortress" bomber to the first pressurized commercial airliner—The Model 307 Stratoliner in 1939 to its flagship 747 jumbo jet to the state of the art, computer-designed 777, The Boeing Company has led the way in the design and manufacture of commercial and military aircraft. Today, The Boeing Company, headquartered in Seattle, Washington, employs two hundred thousand people in over 150 countries and is the most recognized name in aerospace and aviation. By far the largest aerospace company in the world, Boeing divides itself into three business segments: Commercial Airplanes, Military Aircraft and Missiles, and Space and Communications. In 1999, Boeing had record operating revenues of $58.0 billion and profits of $2.3 billion. (See Appendix 1 for recent financial data).

1.2 Boeing Commercial Airplane Group

In 1997, Boeing absorbed the McDonnell Douglas Corporation making the world's largest producer of commercial airplanes even larger. Today, Boeing's Commercial Airplane Group accounts for about two-thirds of the company's revenues. In 1999 alone, Boeing delivered a record 620 airplanes. (See Table 1)

Major Model	Minor Model	Seats	Range (mi)	Aisles	Price (millions $)*	Delivered in 1999
717	-200	106	1580	1	31.5 - 35.5	12
737	-600	110-132	3630	1	36.0 - 44.0	320
	-700	126-149	3800	1	41.5 - 49.0	
	-800	162-189	3370	1	51.0 - 57.5	
	-900	177-189	3140	1	53.5 - 61.0	
757	-200	201-231	4550	1	65.5 - 73.0	67
	-300	243-279	4000	1	73.5 - 81.0	
767	-200	181-255	7655	2	89.0 - 100.0	44
	-300	218-350	7080	2	105.0 - 117.0	
	-400/ER**	245-375	6475	2	115.0 - 127.0	
777	-200/ER	305-440	8860	2	137.0 - 164.0	83
	-300	368-550	6720	2	160.5 - 184.5	
747	-400	416-568	8380	2	167.5 - 210.0	47
						620***

Table 1- A breakdown of Boeing's current commercial aircraft offerings

*Approximate 1999 list prices.
**Extended Range
***Includes 47 legacy McDonnell Douglas planes (MD-80, MD-90, and MD-11)

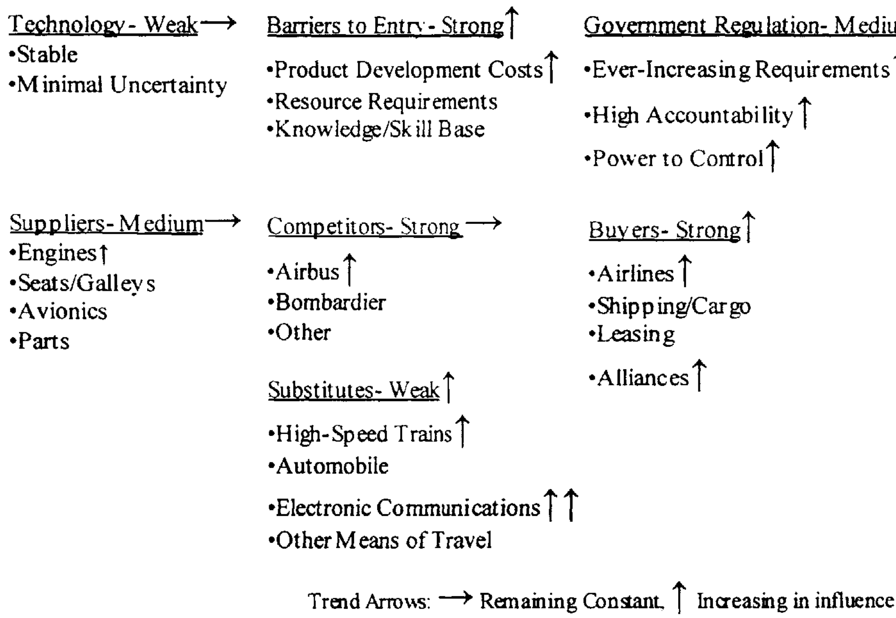
While the parts and sub-components are produced around the globe, all of Boeing's commercial airplanes, with the exception of the McDonnell Douglas-designed 717, are assembled in the Puget Sound area in and around Seattle, Washington. The single-aisle airplanes (737 & 757) are built in Renton, Washington and the larger twin-aisle airplanes (767,777, & 747) are built in Everett, Washington.

1.3 Competition and Competitive Analysis

Today, Boeing is one of two principal aircraft manufacturers in the world. Boeing Commercial Aircraft Group's (BCAG) main competitor, Airbus Industrie, founded in 1967 as a consortium of European aerospace companies, is rapidly approaching fifty percent of the world market. In fact, Airbus surpassed Boeing in airplanes ordered in 1999 for the first time in history. Together, Boeing and Airbus represent nearly all the 100+ seat commercial aircraft sold.

Airbus's rapid ascent in the airplane market over the past few years is attributable to several factors. First, Airbus has the support of several of Europe's wealthiest governments supporting it through subsidies, tax breaks, and favoritism in the sales. The non-public status as a semi-governmental entity enables Airbus to carry out its operations with minimal shareholder scrutiny over its bottom line. Second, Airbus's late entry into the high-volume manufacturing business has freed itself from historical baggage and allowed it to adopt many of the latest manufacturing principles. Third, Airbus's product line, consisting of fewer major models than Boeing, has enabled it to focus its operations on production of these high quality airplane models. Finally, Airbus has the advantage of ramping up its capacity while Boeing has had to continually distribute excess capacity overhead among its products that are still selling. While many at Boeing would like to believe that Airbus's primary advantage comes from its non-public status and governmental support, the reality is that Airbus is a formidable competitor regardless. In fact, Boeing's own difficulties in digesting the McDonnell Douglas and its initially complacent reaction to Airbus caused it to lose money for the first time in recent history in 1997.

Today, Boeing is refocusing its efforts commendably and is taking aim at Airbus. A new financial management team with profit-motivated practices and significant improvements in its operations, especially with the 737NG and 777, has helped steer Boeing back on track. Together, Boeing and Airbus, enter the twenty-first century primed for fierce competition and both capable of reaping incredible rewards. In **Figure 1** we see a



competitive analysis of the major forces surrounding Boeing in the commercial aircraft industry.

Figure 1- A Market Forces Analysis of Boeing as a Player in the Commercial Aircraft Industry

1.4 The 777 Aircraft

In 1990 Boeing launched the 777 Program and after several years of study delivered the first 777-model airplane in 1995. The 777 is the second largest plane in Boeing's fleet, behind the 747, and is the largest of the twin-engine planes. The 777 took several billion dollars to develop and when finished was the most technologically advanced commercial aircraft ever built. Designed entirely by computer, the 777 was the first airplane ever to be assembled without a full-scale prototype. Not only did the 777 represent the latest in aerodynamics, fuel efficiency, and flight capability, but it also incorporated the latest in manufacturability. The 777 was designed with the customer in mind and provided the flexibility to accommodate multiple configurations. In fact, the 777 was designed with *flex-zones* that enabled airlines to install and reinstall interior monuments[1] in a continuum of pre-certified positions. Its passenger capacity ranged from 305 to 550 passengers depending on the configuration and it is sold for between $137 million and nearly $185 million. The flexibility of its design and the relative ease with which airlines could reconfigure planes is a major selling point of the 777.

1.5 Selling the 777: Options and Configurations

The 777 competes mainly with the Airbus A340 model aircraft in the market for long distance intercontinental routes. It distinguishes itself from the A340 by claiming a lower cost of operation enabled by its higher flight speeds and greater fuel efficiency, and as mentioned above, by its configurability. With the 777, prospective airline customers can choose from a wide variety of options and configurations for the aircraft. These choices range from the color and type of cloth on the seats and walls, to the engine manufacturer, to the size, location and features of each galley, to the inflight entertainment systems (IFE) offered in each class of service. Options can be purchased directly from Boeing as *Supplier Furnished Equipment* (SFE) or they can be purchased by the airline and turned over to Boeing for installation as *Buyer Furnished Equipment* (BFE). While the majority of options are SFE, many of the highest impact items such as engines, seats, and inflight entertainment systems are BFE.

1.6 Manufacturing the 777: Airplane Assembly

While Boeing has the capability to deliver a 777 every three days, it takes about fifteen months from the time a customer orders a plane until it receives it. The long lead-time associated with the plane is due to several factors. First, because Boeing designs each plane according to the customer a significant amount of engineering must be done to determine the components necessary to build the plane. Second, Boeing must coordinate thousands of suppliers, as nearly every part is built with a specific customer order in mind. All of these suppliers have their own lead times necessary to deliver their parts. Historically, parts that require frequent redesign and have heavy regulatory hurdles, such

[1] Monuments are galleys, lavatories, closets, stations, or other non-structural units inside the aircraft.

as seats and galleys, have the longest lead times. Finally, Boeing's assembly and flight test times take a few months to complete. The assembly process takes place in Everett, Washington and begins with the assembly of the body structure from fuselage pieces imported from other parts of Boeing and overseas suppliers. Once assembled, the fuselage is moved temporarily from the main assembly bay to be coated in a protective material. After this coating the fuselage is returned to the assembly area where the major systems and components are integrated. In a step called *Final Body Join* the wings, sub-assembled in another area of the factory, are attached to the fuselage along with the landing gear. Once completed the plane can be rolled on its own to the first of three *Final Assembly* positions. The plane spends a fixed period of time in each position. The first two positions consist of the installation of the aircraft systems and customer specific "stuffing." In the final position, main tasks on the exterior and interior of the plane are completed. The external work includes the hanging of the engines as well as the thorough testing of the flight systems, wings, and landing gear. In the interiors of the plane the customer specific interior options and configurations are installed. Any work not completed in the factory after the allotted time in the third position gets completed out in the field where the flight testing occurs. The flight test process takes approximately four weeks on average. It involves rigorous testing of all systems and their integration and at least two test flights.

Chapter 2: Discovery and Problem Identification

2.1 Interview Results

The first few weeks of the project consisted of numerous interviews with senior managers from across BCAG organization. Though the originators and sponsors of the project had conceived of the project based on intuition and years of relevant experience, they were asking us to actually define the problem that they were sensing and then to go about recommending ways in which to address the problem. The first steps were to poll the relevant stakeholders in the 777 program to understand the full scope of the business. This entailed obtaining a cursory understanding of all parts of the business, from the initial customer order to the delivery of each aircraft and the steps in between. In doing so we could develop a better understanding of the problem, as well as some personal intuition regarding the different angles and frustrations that different groups had on the subject. In **Figure 2** below I have outlined some representative comments made by the individuals involved in the 777 program.

What People Were Saying:

"Boeing doesn't discretely collect the cost of a single airplane. A block of 50 airplanes- YES; a single airplane- NO."
-Finance Manager

"I know I like to build Airline ABC, and I know I don't like to build Airline XYZ, but I don't know why."
-Operations Manager

"We feel a lot of pain in Interiors, every plane has a different configuration."
-Manufacturing Manager

"We have very little, if any, information on individual configuration costs."
-Sales Manager

Figure 2- A sampling of quotes from around Boeing

One basic conclusion, which could be drawn from these interviews, was that the cost of a single airplane is not widely understood. The best approximations on cost were built from averages and rough estimates. In fact, most costing was done in blocks of 50 aircraft and the actual numbers are learned in retrospect. When there was good information on cost it was often found in pockets and was not to be distributed to other departments and groups. As the comments suggests, identifying the drivers of cost of a single aircraft continually presented problems to Boeing.

The second conclusion that could be drawn centered on the multiple configurations and options that were offered with the 777. While the 777 was designed to offer tremendous flexibility it was not clear that the supporting systems and operational infrastructure in the manufacturing areas could handle the amount of product variation that the sales and marketing groups were offering to customers. Here, numerous frustrations were expressed by operational managers regarding the uncertainty of the workload in each of the factory shops, particularly in the interiors installation shop. These managers found it exceedingly difficult to predict the resources necessary to build a particular aircraft. There were many suggestions to come up with option reduction strategies to help alleviate the pain that these shops were experiencing. Rather than suggesting cuts in the product offerings, a hot button among many of the sales and market managers, we instead recognize the more important need to bridge the gap of information between the build process that deals with cost and the sales process that deals with price.

Presently the method for pricing options and configurations is to price each individually. The assembly, installation, and integration of options are considered to part of the base price of the aircraft. A pre-determined code is given to each aircraft depending on the expected complexity of the configuration. A *Code 1* airplane, also known as a customer introduction, is the first of a particular configuration that Boeing builds for a customer, and is accordingly allocated a significant number of engineering and manufacturing labor units for the complexities associated with being the first of its kind. A typical follow-on aircraft, a previously built configuration, is a *Code 4* aircraft and is granted a minimal number of labor units as its assembly is considered to be relatively smooth. *Codes 2* and *Code 3* planes involve are minor alterations to existing configuration, such as the addition of crew rests or new supplier of business class seats and typically have labor units allocated somewhere in between that of a *Code 1* or *Code 4*. These codes and the option prices are part of the formula Boeing uses to price its airplanes. Any discounts offered may or may not be related to the complexity of the option package or configuration.

Given these findings, we focused our efforts on establishing and understanding what actually drives the variation in cost of a single aircraft. This is based on the premise that to effectively build and sell individual planes for a maximum profit the individual costs must be understood. If we could establish the drivers of variation in cost we could then determine where in the build process the information came available and route it to divisions that may be able to make more informed decisions based on that information. It was the hope of the project sponsors that much of the variation could be explained by inherent characteristics of the configuration and options such that the sales team would have cost information at the onset of the sales process and the contract negotiations. Thus, we seek to explain what portion of the variation in cost is customer-driven and what portion is systemic to the process.

> ***Customer-Driven Variation:*** This is variation caused by the customer and its choice of options and configurations. It includes all practices unique to a particular customer during the build process, such as the way they handle inspections, delivery and other mechanisms that may affect the cost of the plane. It also encompasses all factors that might be known at the time of sale (e.g. approximately unit number, number of previously built configurations, etc.) In other words, we define customer-driven various to include all information about the aircraft at the time of sale before the plane is actually built.
>
> ***Systemic Variation:*** This is variation caused by Boeing's own processes that may contain inherent variability. This is the variation resulting from circumstances that could not be foreseen at the time the order for the plane is placed. (e.g. failed tests, late part arrival, part shortages, workforce slowdowns, etc.) This information will not be known at the time of the sale of the plane.

The distinction between the two types of variation outlined above is critical to helping Boeing focus its efforts appropriately. The necessary prescriptive measures to take if Boeing's processes account for much of the variation in the cost of the plane are far different from those which could be implemented if the processes are stable and there is upfront knowledge on the cost at the time the order is placed.

Thus, in light of these interviews, it makes sense to attempt to rationalize these problems Boeing is facing. With the appropriate investigation it may be possible to identify the essence of these problems and offer insight into the types of measures that Boeing might be able to alleviate the issues they are encountering. In the remainder of this paper we seek to explain this variation, or some portion of it, and to recommend to Boeing appropriate next steps in solving this problem. More specifically, we present the following three contentions that we will investigate in this paper:

(i) There is significant variation in the cost of individual airplanes that is not being picked up by the current costing processes and it is worthwhile for Boeing to further understand these cost fluctuations.

(ii) Most of the variation in cost of the plane is attributable to the variation in cost of the installation of the interiors of the plane.

(iii) Most of the variation in cost of the installation of the interiors, and thereby in the cost of the assembly of the plane, is driven by the customers' choice of particular interior options and configurations, and can be explained by a combination of learning effects[2] and customer-driven variables.

The first contention claims that while the learning curve is an adequate first-order predictor of the cost of assembly of an airplane Boeing still suffers from its present lack of precision. Our second claim isolates the interior shop in the factory as the origin of most of the total factory variation. The third contention postulates that the inclusion or exclusion of particular options, features, and configurations of a particular plane can systematically explain much of the variation in the interior shop. Consequently, we develop an empirical model to validate (iii) and contend that there is considerable stability and predictability to Boeing's assembly operations. Together these claims also imply that if (i), (ii), and (iii) can be established then there may be significant opportunities to improve Boeing's bottom line.

The remainder of this chapter focuses on the first two propositions. The next chapter addresses the validity of (iii) by developing an empirical model.

---

[2] Learning effects are factors where an organization or other human-involved process gets better or worse over time or repetition.

2.2 Estimating Cost

Cost, in dollars, was not made available for use in this project to protect Boeing's strategic interests, so instead for the purposes of this project we use labor units as a substitute for dollars. Also, to protect Boeing's interests, we will not disclose any nominal values for the build labor units but we will be able to display the relative magnitudes of the assembly efforts as they were measured.

2.3 Cost Assumptions

The measurement of airplane cost in labor units has several implications but is widely considered to be an appropriate indicator of cost. First, the labor units measured are direct labor units. They do not include indirect, support, or administrative labor units that will obviously accompany every airline. We therefore must make the assumption that these auxiliary labor units maintain a relatively constant proportion to the direct labor units.

Another major point of importance is that our efforts in measuring are only focused on the final assemblies and installations of the aircraft. There are two corollary points to be made. Because of the lack of engineering data[3] we were unable to include engineering labor units in the costs of each plane. Thus, there is additional cost in each plane that probably varies because the customer-driven options and configurations that are selected have significant engineering requirements before installation. While it is commonly thought that that engineering labor units would accentuate the plane-to-plane variation in accordance with the installation efforts, we will leave it for a follow on study to make that determination.

The second resulting implication is that all part and subassembly costs have also been excluded from the model. Most of the Boeing owned factories of parts and subassemblies do not have the granularity in their systems to identify individual plane costs. For those that do, and for external suppliers, it will be assumed that the costs can be

[3] Engineering labor units are kept for Code 1 Customer introductions, but all follow on models are rolled up together which obscures plane-to-plane visibility. We will incorporate code 1 engineering labor units into our analysis, but the smaller sample size may be limiting.

brought forward to the airline customer and accurately represented in the costs of the plane. In other words, if the part cost is well understood then it is assumed that Boeing can capture that cost and pass it on to its customers appropriately. To illustrate this point, consider an example of business class seats. Two airlines may order their business class seats from two different suppliers. The first customer orders expensive seats with leather and advanced IFE. The second orders a more basic seat. The costs of these seats will be different, but they will be well understood because they have a price from the supplier that can be included in the catalog price for the customer to make an informed decision based on their need. However, the cost of installation for these seats is what is not understood as well. Boeing's current method of estimating cost assumes the cost of installation to be identical. As one Boeing executive put it, the part costs are well understood, but the glue that puts them together which is where we lack the visibility. Thus, here is where our efforts are focused.

2.4 Magnitude of the Problem

Our first step is to find and verify that the perceived variation is in fact real and significant. Undoubtedly, we look at total factory labor units to build each plane as the precise measure needed to estimate the relative cost of each plane so that we could monitor the plane-to-plane variation in cost per the discussion above. **Figure 3** represents the total labor units it took to carry out the final assembly and installations for each plane. From this chart, we observe the dramatic learning curve associated with the airplane manufacturing process. The learning curve has historically been a powerful tool for predicting the cost of an individual airplane. Unfortunately, the past success can have a detrimental effect if it instills complacency. While all planes are significant to our study, the examination of the entire sample set masks much of the variation[4]. Instead, we seek greater granularity to see the plane-to-plane variation in labor units.

[4] While it is merely a question of scale, much of the practical communication and knowledge sharing at Boeing is accomplished visually, not statistically, through charts on the entire learning curve similar to Figure 3 and much of the awareness of granular details is lost. Thus, in Figure 4, we highlight only the last fifty planes and take out the 777-300's to visually (as well as statistically) communicate the presence of significant variation. Note, as mentioned in the text, we also minimize the effects of the learning curve by only taking examining recently built planes.

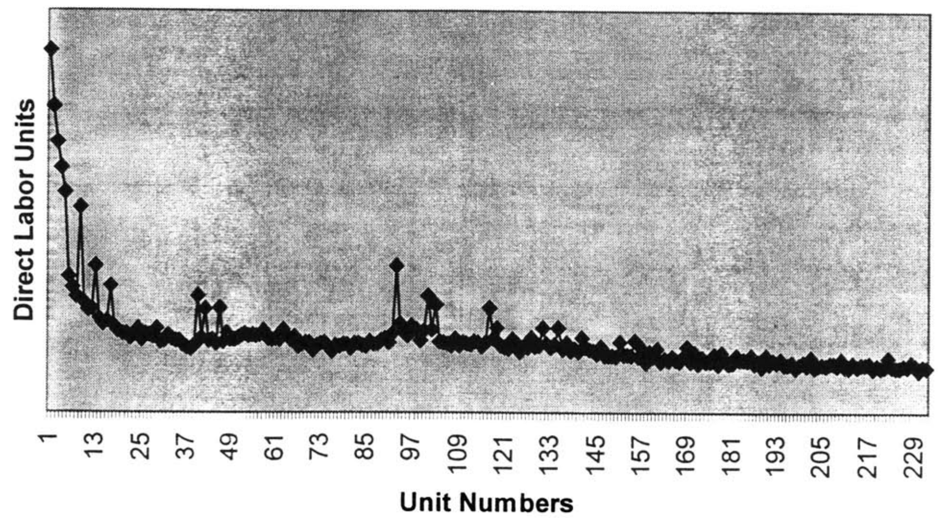


Figure 3- Total Factory Labor Units to Assemble the 777 by Unit Number.

To minimize the effects of the learning curve on the data we observe the tail end of the data set. As expected, this smaller sample of planes still has significant swings of greater than 15% above and below the mean number of labor units. However, we must acknowledge that the 777-300 model aircraft also causes some of the variation[5], and thus we remove the 777-300's in **Figure 4** below. This chart captures the plane-to-plane variation by focusing on only the last fifty non-777-300 planes of the sample where the learning curve effects are minimal. For the purposes of presentation, isolating the last fifty non-777-300 planes also enables us to enhance the visual display of the variation by increasing the scale of the chart.[6] When we remove the 777-300's from the sample data, we still observe significant swings in the total number of factory labor units in the build process. Statistically, we have calculated the likely range of total labor units as the mean plus or minus three times the standard deviation ($\mu \pm 3\sigma$). For this set of planes $3\sigma/\mu \approx$ 15%. This means that the total factory cost fluctuates 15% above and below the mean. Another way of interpreting this volatility is that 32% of the time an airplane's total assembly cost will be further than 5% from the mean.

[5] The 777-300 aircraft that are considerably larger (~20%) than the 777-200 and 777-2ER models.

[6] Obviously, we must also support the magnitude of the variation with non-disclosing summary statistics as well.

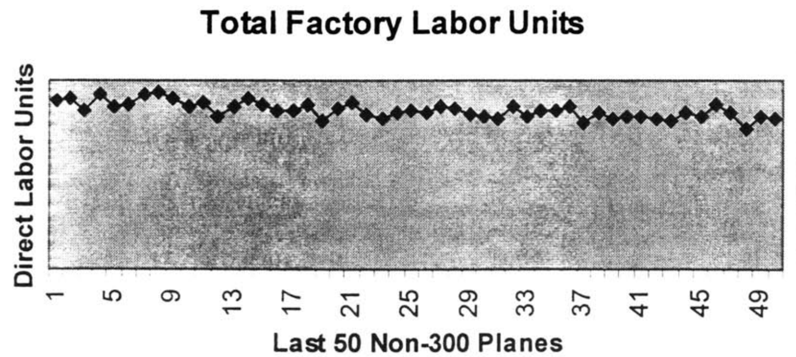


Figure 4- Total factory labor units to assemble 777 ($3\sigma/\mu = 15\%$)[7]

2.5 Implications of the Variance

One final issue must be addressed, before we began to analyze the interior labor units for variation and cost drivers: The implications of the observed variance. Consider that the variation was not significant to the overall manufacturing and selling process to an airplane. In that case, any insight into the drivers of variation might not impact fundamental business decisions. Thus, we must, at least to some basic degree, establish that the variation observed is problematic to Boeing at the bottom line. Thus in this section we will outline several factors as to how the variation has an extremely negative impact to Boeings profitability and customer relationships.

The basic operating concept behind any manufacturing company is to sell product at a price higher than its cost. The more a company understands the subtleties of its cost structure, and the better it understands the intricacies of its customers' willingness to pay, the better it can adjust its own selling practices to maximize profits. As established above, Boeing's method for costing its planes lacks granularity in estimating assembly costs. Even assuming that Boeing has complete information with respect to its customers' willingness to pay, an improvement in the understanding of its cost can only be beneficial. Without divulging the actual swing in labor units that Boeing sees from plane to plane, the impact of these labor units is significant, less so when compared to the

[7] Note that the vertical access on this chart goes from 0 to C. In order to maintain the confidentiality of the data we do not disclose C.

overall cost of a plane, but vital when considered at the margin[8]. The margins are not the only impact to Boeing's operations. Variation inhibits the efficiency of learning by interrupting otherwise repeatable processes. The variability of labor units also requires Boeing to bear excess capacity and flexible stations to accommodate the swings for each plane. Additional insights on cost and variation could be translated into tailored capital investments and other operation decision-making practices. There is even a lost opportunity cost in the selling process. If Boeing had information about the drivers of this cost variation, it could influence customers toward lowered cost options, when they might otherwise be indifferent. Furthermore, if Boeing were willing to pass on some of the realized savings associated with their better command of costs then ultimately these savings could manifest themselves as lowering operating costs to the airlines, which would in turn spur demand.

In summary, by failing to completely grasp the drivers of this variation, Boeing must resort to using averages and estimates to determine its prices. The detrimental consequences are clear. Some customers subsidize others and simultaneously Boeing is losing out on potential profits.

2.6 Interior Options and Configurations Drive the Variation

While bearing little scientific significance, we use the option catalog to highlight areas with the broadest option offerings by ranking those with the most pages per chapter. A Pareto chart of the number of pages in each chapter of the option catalog, quickly adds merit to our initial claim that if a significant portion of the variation in the cost of the 777 comes from inherent plane-to-plane differences in the selected options and configurations then it specifically comes from the interior options (e.g. premium seats, economy-class seats, galleys, lavatories, and other interior features). Over 50% of both the 777-200/2ER and 777-300 catalogs are dedicated to the Equipment Furnishings chapter. This is the chapter from which a customer selects its interior options and configurations.

[8] While Boeing would not disclose its margins, the author has made basic assumptions about the margins from publicly available financial material.

Clearly to validate our second contention (ii) we must demonstrate more than the relative breadth of offerings of the interior options and configurations. We must also show that the breadth of offerings translates into highly variable assembly times. Fortunately our data gives us visibility into the components of the total factory labor units. The total factory labor units, as depicted in Figure 4, above, are the sum of eleven shops in the factory. Of these eleven shops about half are dedicated to the assembly of the *Body Structures* (i.e. body assembly, wing-body join, and seal, test, and paint). The other half of the shops are dedicated to the *Final Assembly* that entails the installation of systems, doors, exterior components, and the aircraft interiors. While most shops openly post their individual shop's performance, rarely have all shops been considered as parts of the same total. Figure 5 and Figure 6, on the next page, take the individual shop labor units from within the factory, adjust them to a common scale, and put them side by side for comparison.

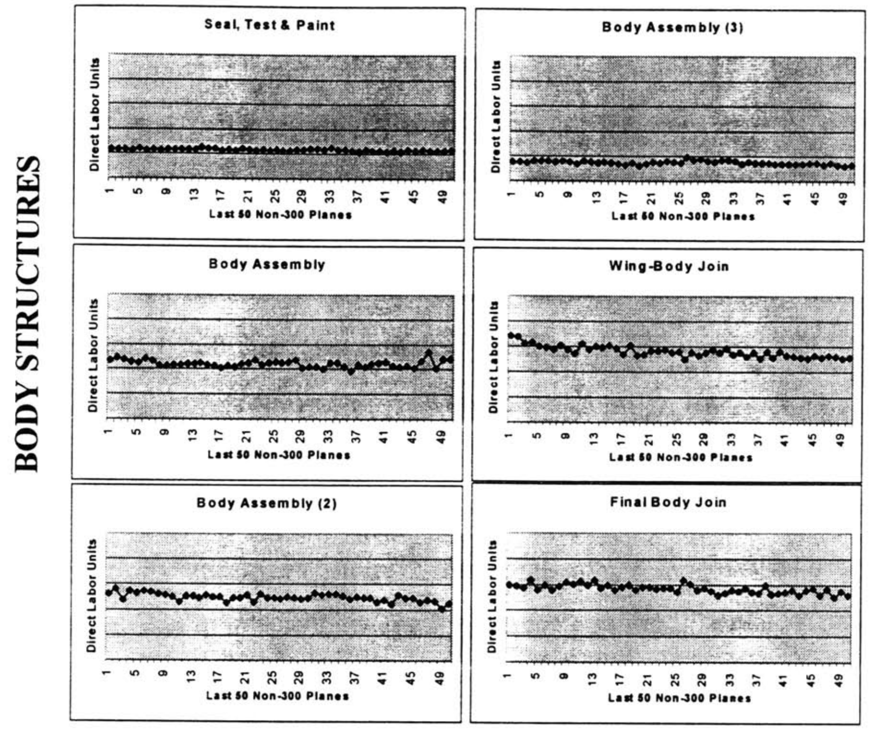
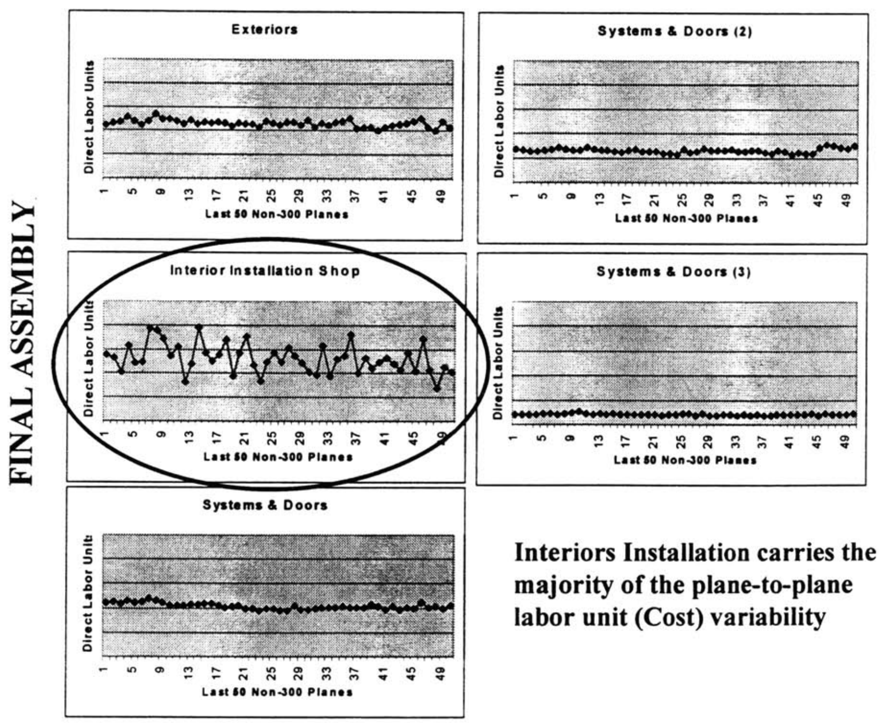


Figure 5- Individual Shop Labor Units for Body Structures[9]



[9] Note that in Figure 5 and Figure 6 each graph is set to a common scale for comparison purposes (i.e. the vertical axis is set from 0 to C Labor units in each of the 11 graphs).

Figure 6- Individual Shop Labor Units for Final Assembly

Location	**Coefficient of Variation (σ/μ)**
Entire Factory	0.05
Body Structures	
Seal, Test & Paint	0.03
Body Assembly	0.06
Body Assembly (2)	0.06
Body Assembly (3)	0.09
Wing-Body Join	0.07
Final Body join	0.06
Final Assembly	
Exteriors	0.06
Interior Installation	0.22
Systems & Doors	0.06
Systems & Doors (2)	0.07
Systems & Doors (3)	0.07

Table 2- Breakdown of Standard Deviations by Factory Shop

The results are clear and easily interpreted. The interior installations shop (*Interiors*) accounts for nearly all of the variation in the factory. In comparison, other shops are relatively stable and predictable. The interior shop labor units, on the other hand, swing up and down as much as 50% from their mean.

Accounting for the 777-300 models, we can show that the interiors shop is the only shop whose variation exceeds the control limits of the total factory's control limits.[10] This implies that none of the other individual shops significantly affect the volatility of the overall factory while the interior shop does. Furthermore, it can also be shown that the

[10] See Appendix 3 for control charts and statistical derivations of variation.

interiors shop accounts for the large majority of the variation in the factory. From **Table 2** we see that the standard deviation of the interior labor units is nearly threefold of that of any other shop and it has the highest standard deviation of differences between its actual number and it budget, meaning that to Boeing interior installation labor units are by far the hardest to predict. In fact, when we subtract out the interior labor units from the factory totals we can predict the remaining labor units with a remarkably high degree of accuracy with a multivariate linear regression on only three variables. For this analysis we use three independent variables that are universally considered to be significant predictors of assembly time: learning curve, the 777-300, and flight test.

Summary of Fit	**Other 10 Shops**	**Interiors**
R-Square	0.87	0.46
R-Square Adjusted	0.87	0.45
Root Mean Square Error/Mean	0.09	0.25
Sample Size (n)	150	150
Parameter Estimates	**t-Ratio[11]**	
Intercept	28.00	12.24
ln(Unit Number)	-21.11	-9.46
777-300	7.53	3.00
Flight Test	13.48	-7.91

Table 3- Results of a Multivariate Linear Regression Model Run with three independent variables to Predict Total Factory Labor Units less Interior Labor Units (i.e. the other 10 Shops) as compared to the Interiors Labor Units.[12]

Consistent with our earlier findings, we find the interiors shop contains much more variation than the other shops in the factory combined. It is not surprising that all three variables are highly significant in both cases and yet the average t-Ratio in the first case

[11] We report only the t-Ratios to protect the confidentiality of the data.
[12] This regression model is intended to illustrate the relative ease with which we can predict the other 10 factory shops, and we acknowledge that there are other parameters that could be included that may increase the model's validity. The last 150 777 aircraft were chosen for the regression analysis to be consistent with the more thorough model developed in the next chapter.

is more than double that of the interiors shop. The results reveal that these three variables explain almost all of the systematic variance in the ten shops. This contrasts with the interiors shop where much of the variation remains unexplained by these variables. Interestingly, the Flight Test t-Ratios have opposite signs in the two models. This can be explained because flight test airplanes are built without interiors and yet tend to be more complicated for the other ten shops. Finally, it should also be noted that the summation of the ten shops could have a dampening effect on the total volatility. In other words, much of the unsystematic error will cancel out over the ten shops and will remain present in the interiors. While this would cause similar results the earlier findings are not consistent with this. Thus, from these findings, we validate our second contention and hold that most of the variation in the factory is borne by the interiors shop.

Thus, as the original project sponsors had hypothesized, if we can account for the variation in the interiors installation shop we can account for much of the variation in the cost of the overall plane. Any insights gained about what factors drive interior costs can then be distributed to relevant decision makers throughout the company to make more informed business decisions. In the next chapter we will expand upon our regression model above to include factors that specifically influence (or are believed to influence) the interiors shop assembly costs.

Chapter 3: Interiors Shop Model

3.1 Understanding the Variation: Nature of the Model

The following section outlines the basic framework of the model used to predict the labor units of given airplane's interior installation. Our goal with this model is to validate our third contention that states that the variation in the cost of the installation of the interiors can be largely explained by customer-driven variables, learning and memory effects variables, and other variables known in advance of assembly. If the contention is correct that Boeing processes are stable and predictable and if there is truth to the notion that cost variance is driven by inherent differences in each plane's unique options, configurations and circumstances, then it stands to reason that a systematic methodology could be used to estimate the cost of an individual plane. It has been suggested that there is a base cost for each plane and that influencing factors that increase or decrease the total expected labor units cause deviations from that base cost. It is this type of theory that lends itself to our model, which may be represented as a multivariate linear regression. Our model takes the following form:

$$Y = C + W_1X_1 + W_2X_2 + \ldots + W_nX_n$$

Where Y, the dependent variable, is the actual number of labor units recorded by the interiors shop for a given plane's interior installation. C, the intercept, is the base or average number of labor units of a plane with no special circumstances[13]. X_1 through X_n are factors that contribute to the overall number of labor units whether positively or negatively. Finally, W_1 through W_n, the coefficients of the model, represent the relative impact that each factor has on the overall number of labor units for a given plane's interior installation. These coefficients are signed to indicate a positive or negative impact on the overall model. Therefore, the aggregate sum of the positive and negative influences (coefficients times factors) of the model determines the actual number of labor units in the interiors shop.

[13] Note that merely being down the learning curve is considered a special circumstance.

3.1.1 Identification of Variables

Initially, potential factors were identified through interviews, recommendations, and examination of the features of an airplane. Of these potential factors many were not collectible. Those that were not collected were because of incomplete data sets or confidentiality, or the unreliability of the sources[14]. Even among the collected data there were sometimes holes or gaps, particularly with the earliest built planes where. Of the variables that remained many show signs of a high degree of collinearity. We attribute this to the many common groupings of certain options and configurations. Following, the preliminary results of our inquiries, and after careful inspection of a correlation matrix, we narrowed down the potential factors to 18 potential variables.

Eight of the variables can be described as customer-driven variable. These are factors whose value is specified by the customer at the time of the order: 777-300 is a binary variable indicating the major model of the aircraft. Premium Seats Delivered, First Class Seats Delivered, and Business Class Seats Delivered are the number of seats in each respective class of service that actually get installed by Boeing[15]. Video Control Centers and Purser Workstations Delivered (VCC's Delivered) are the combined total of these units installed by Boeing. Crew Rest is the total number of crew rests installed by Boeing. The Gaseous variable identifies those planes with gaseous oxygen containers instead of oxygen canisters. Finally, the Number of Seat Sections is the number of distinct seating areas whether divided by partitions, monuments, or classes.

There were five variables identified as learning effects or memory variables. These variables involve the passage of time or the repetition of work. ln(Unit Number) describes the natural logarithm of the ordinal sequence in which the plane was built with respect to all 777's. ln(Airline Order) describes the natural logarithm of the ordinal sequence in which the plane was built with respect to all other planes ordered by the same airline. ln(Configuration Order) describes the natural logarithm of the ordinal sequence in

[14] See Appendix 2 for a complete list of the variables.

[15] There have been several planes orders with identified seat counts and yet the airline, not Boeing installs the seats.

which the plane was built with respect to all other identical configurations[16]. Finally we identified the ln(Gap Between Last Configuration) and ln(Gap between Last Airline) which represented the natural logarithm of the number of planes between the current one and the last one (configuration or airline respectively) to be built. All planes with new configurations and all new airlines were given a default value of 500.

The remaining five variables did not fit well with either category. Late BFE Maximum Days Late represented the maximum number of days late that any BFE was delivered to Boeing. The number of defects reported by customer inspections was a measure of the customers' involvement in the manufacturing process and their level of scrutiny in accepting the plane. The labor units of the previous plane built, the rate of the line at the time the plane went through the factory, and whether or not the aircraft was a flight test plane or not rounded out the rest of the variables.

3.1.2 Data Collection

Our sample set of planes includes all but two of the first 234 777 planes that Boeing had built. Only the first plane (never sold) and one airplane sold confidentially without an interior were excluded from the sample. We capped our sample at 234 planes in order to facilitate a one-time collection of data. Table 4 includes some basic facts about the sample set of airplanes:

First Plane Delivered	May 1995
Last Plane Delivered	August 1999
Number of 777-200's	68
Number of 777-2ER's	140
Number of 777-300's	24
Number of Airline Customers	22
Number of Unique Configurations	42

Table 4- Overview statistics of sample set of airplanes.

Unfortunately, our data set was incomplete because Boeing did not collect several of our variables in the first 80 or so airplanes built. Thus, for the rest of our analyses we have used the final 150 aircraft in the sample set (sample set Unit Numbers 85 to 234). We

[16] There were no instances where two airlines ordered identical configurations.

also saw a trend of increasing labor units from unit numbers 60-80 that were difficult to explain and we felt that our attempts to explain the variation would be better if we focused on more recent aircraft. We are comfortable with this because the sample size is still relatively large and the later planes are more indicative of current manufacturing practices. It should be noted that the collection of data for this model was not encompassing and with more time and resources a more complete analysis could be done. While the employees at Boeing were exceedingly helpful in providing data where they could, there were instances where certain data was unobtainable, incomplete, or not captured by unit number as was required for the study. Despite these caveats, the data that was collected was extremely rich in content and thorough in coverage of the major factors in the manufacturing process. As we progressed with our analysis we believe this data was able to shed insightful and unique observations about the drivers of variation of the cost of an airplane.

3.1.3 Analysis of Data

A standard least squares regression was performed using all 18 selected variables. From the preliminary runs of the analysis 14 variables were assigned coefficients that were plausible and in line with expectations. Four variables were dropped from the analysis as they consistently failed to produce significant coefficients.

3.2 Model Results

Table 5 lists the results of the model beginning with the calculated coefficients and intercept estimation. In order to respect the confidentiality of the data, only the t-Ratios (t-values) are reported along with the summary statistics of the overall model fit. For the overall results, not surprisingly, there was no dominant effect. Instead, there was a distribution of factors, all of which contributed significantly to the outcome.

Customer-Driven Variation	t-Ratio[17]
777-300	5.31
Premium Seats Del'd	2.56
First Class Seats Del'd	5.27
Business Class Seats Del'd	2.00
Crews Delivered	4.09
Gaseous Oxygen System	1.74
VCC's Delivered	2.04
# of Seat Sections	-2.28
Learning Effects	
ln(Unit Number)	-8.49
ln(Airline Order)	-2.74
ln(Configuration Order)	-3.12
Other	
Flight Test	-8.34
Late Seats (Max Days Late)	3.23
Defects	3.13
Intercept	9.63
Model Summary Statistics	
R-Square	0.82
R-Square Adjusted	0.80
Root MSE/Mean	0.15

Table 5- Interiors Shop Model Results

[17] We report on the t-Ratios to protect the confidentiality of the data

3.2.1 Evaluation of Variables

In Table 5 we have separated these variables into three categories: Learning Effects, Customer-Driven, and Other. In the first category, Learning Effects, we find confirmation that there is a significant learning curve that reflects the total number of 777 planes built. Also not surprisingly, we find that the interiors shop improves with each configuration. In other words, the more identical configurations the shop builds the faster it can build each one. Interestingly, the model also highlights a learning curve with each airline, irrespective of configuration. This could possibly be explained that an airline becomes more accustomed to Boeing's manufacturing practices and therefore subsequent airplanes tend to flow more smoothly through the interior installation process. In all learning cases we find, as we would have expected, negative coefficients. This indicates that the interiors installation shop is improving with each plane it builds and that it remembers previous configurations and airlines so that subsequent planes do not take as long to build.

In the second category, the customer-driven, there are eight variables that were highly likely to be driving the interior labor units changes. While perhaps they are all intuitively obvious, they begin to establish a concrete method for characterizing individual configurations by focusing on those element which seem to factor highly in the cost of assembly. As expected, we see the dominant variable in this category being the influence of the 777-300. Customers who choose the larger version of the 777 family select an aircraft that consistently takes longer to build. Accordingly, Boeing has long been aware of the added cost of the 777-300 and attempts to reflect the extra effort in the list price. The next three variables, VCC's Delivered, Crew Rests Delivered, and Gaseous Oxygen, all are consistent with expectations. Each of these features has been thought to be particularly costly. According to the t-Ratios, the crew rests are the most labor intensive of the three, followed closely by the presence of gaseous oxygen systems. Slightly surprising is the fact that the Video Control Centers and Purser Workstations appear to be slightly easier. Because we did not have data on inflight entertainment systems, we would have thought much of their difficulty would have been picked up by the presence of VCC's Delivered. As we shall see, one explanation for why this may not be as significant as expected is that the effects of IFE are also picked up by the seat variables. The seat variables also consistently matched our expectations. The more highly customized the class of seats the greater the absolute value of the factor coefficient. Thus, every premium seat contributed the greatest number of labor units to the model, followed closely by the standard first class seats, and then the business class seats. Our interpretation of these seat variables is that they are likely picking up much of the complexity associated with the particular level of service in the class. In other words, these three variables are specifically indicating the incremental cost of an additional seat, but rather that are reflecting the amount of cabin real estate occupied by a particular class of service. In this way, these variables account for IFE along with any of the other details that inevitably make the higher classes subject to more scrutiny. The final variable, whose results are perhaps a bit more interesting to interpret is the seat sections variable. Interestingly, the more distinct seating sections in the configuration, the easier the build process seems to go. This may be counterintuitive to some who feel that more sections reflect greater complexity. Our interpretation is that distinct seating sections may have some effect of damage control. Installation problems may tend not to spill over into other sections, or rather problems get contained to smaller areas and more work can be completed elsewhere in the plane because of the partitioning. This final variable is certainly subject to questioning and undoubtedly more monitoring of the effect is needed.

In the final category, we see three other variables impact the total cost of a configuration. Most notably we see that importance of indicating a Flight Test variable. Again these planes are delivered without an interior and correspondingly there is a significant drop in total labor units whenever an aircraft is used for flight test[18]. While this variable does not offer new insight it is necessary to account for the flight test planes so that we can learn from the other variables. Again, the remaining variables may seem intuitively obvious, and the model now confirms many of the notions held by the Boeing production world, but now adds a magnitude and relative importance of each. We now have an estimate of the relative cost of each day BFE arrives late and how long each defect takes to address.

[18] It should be noted that flight test planes are eventually fitted with interiors, but those installations are not carried out by the interiors shop.

This information should be extremely beneficial to the groups that design programs and processes around theses topics.

Variables
ln(Gap Last Configuration)
ln(Gap Last Airline)
Rate
Interior Labor Units Previous Aircraft

Table 6- Variables determined by the regression model to be insignificant.

Finally, our model highlights several findings of non-significance that seem to answer some longstanding questions about the variables in question. While the configuration variables were somewhat sensitive to the exclusion or inclusion of other confounding variables, the variables in that were found to be insignificant were consistently so. This consistency was helped in part to the low correlation of these variables with respect to other configuration variables. The first two variables speak highly of Boeing's ability to retain information about previously completed aircraft as the gap between the previous configuration and the gap between the last plane from the same airline do not seem to factor into the interior labor units of the current plane. With the rate variable there was some evidence to suggest that slower rates increased the time it took to complete the interior installation, but it could not be shown to do so consistently or significantly. Finally, it had been suspected that a particularly onerous aircraft could affect the aircraft being assembled immediately after it. This might be because of slow downs, delays or lost time, but this model offers no evidence to suggest that is happening.

3.2.2 Overall Evaluation of Fit

We are particularly pleased with the following results yet we must also be cautious with our interpretation. Overall, with an R-Square = 0.82 and an R-Square Adjusted = 0.80, we were able to explain much of the interior shop's variation with the variables we had in the model. Furthermore the estimated error of prediction is within 1000 labor units. Of the fourteen significant variables, twelve are known in advance of production and nine of those are customer-driven. All variables have coefficients that are significant at the 90% confidence interval. All but one of the coefficients are found to be significantly different from zero at the 95% confidence interval. In fact, ten variables (when counting the intercept) have parameter estimates significant at the 99% level. As we have mentioned before, we believe that further collection of other variables that were not available at the time of our study, would only yield a more explanatory model.

3.2.3 Model Validation

To confirm the validity of the model we randomly selected 100 of the 150 planes from the overall sample set. We then used the resulting regression information to predict values for the remaining 50 planes' interior labor units. We then compared these results to the budget numbers that Boeing used to estimate the interior labor units. Results of this comparison, shown in Table 7, are staggering. While the results of the model were far from perfect, they were a significant improvement over Boeing's present estimation method[19].

Measurement	Our Model	Budget
R-Squared	0.87	0.13
Mean Average Percentage Error	11%	28%
Mean Average Error	715 Labor Units	2086 Labor Units

Table 7- Results of model predictions as compared to 777 budget.

3.2.4 Alternative Model

Our model intentionally left out the variables for individual airlines because of the high correlations they had with many of the configuration variables. Nonetheless, there is one particular airline, that when added to the model was also highly significant. According to this model the airline had a fairly complex configuration, but certainly not the most complex. This leads us to believe that there are still yet other drivers of cost that are not

[19] It must be noted that Boeing has recently implemented a new method for estimated the interior labor units. At the time of this project the implementation of the effort was just beginning and there was not yet enough data to make conclusion as to its effectiveness. This effort, while promising, is limited in scope to be only a tool to be used for factory scheduling purposes and not for financial cost estimation.

yet well-understood and further explanation of the cost of this airlines' planes is needed. It seems unfair to price higher for that particular airline because of itself, but there is also probably a lot that can be learned about the missing drivers of cost by investigating the particular configurations in depth.

3.3 Interpretation of Results

At the highest levels these results indicate that there is a significant opportunity for Boeing to achieve a higher level of cost forecast accuracy given its current production system. While a *prima facie* examination of Boeing's manufacturing practices suggests that the swings in production labor units for the 777 are erratic and unpredictable, there is substantial evidence from these results that they are in fact stable and instead it is the variation in the product that drives the variation in the cost. Thus, we validate our final contention (iii). Clearly we have promising evidence about those characteristics that drive the cost of the 777, but we must also admonish that there are several notable omissions from our model that clearly affect the cost of the aircraft. First, the individual estimate on some of the variables could be misinterpreted to be an actual cost for those particular items. Instead, they should be seen as components necessary to characterize the entire configuration of the plane. Just as galleys and lavatories tend to have constant ratio within each of the classes, in-flight entertainment systems have also been left out of the model and yet they undoubtedly affect the installation times of the different classes of seats. As we see in the model highly customized (Premium) seats tend to contribute more to cost than do standard first class seats and the standard first class seats are more than the business class seats. It is likely that these figures take into account, not only the increase in complexity of the seats themselves, but also the increase in complexity of the other options which track them closely (galleys, lavatories, and IFE).

A second noteworthy point is that while some models have been predicted nearly perfectly, others were significantly off the mark and need to be examined in more detail to find out why. Note only might further investigation identify other drivers of cost variation, but it also might help fine-tune the understanding of the variables we currently have identified.

The final significant result of the model is the apparent unimportance of the four variables identified as non-significant. While there were many people at Boeing who had questioned whether the gap between configurations or airlines, or the line rate, or the difficulty of the previous aircraft would affect the cost of an aircraft, the model strongly suggests that these parameters do not significantly affect the cost of the airplane. The consequences of these variables will be addressed in more detail in the recommendations section, but it also important to be noted at this time.

Chapter 4: Recommendations

In the following chapter we make a series of recommendations as to what The Boeing Commercial Airplane Group can do with our analyses. From the outset we want to make a clear distinction between two types of measures that can be taken. In the first section of this chapter we discuss some of the measures Boeing can take that acknowledge the variation. By acknowledging the variation, we mean for it to be a foregone conclusion that the variation will continue indefinitely as a consequence of the breadth of the offering of options and the inherent differences in the manufacturability of each configuration. Boeing can then employ steps that take the known variation into account and thereby make better decisions. As mentioned above, there are currently many sensitive issues surrounding the current set of options, configurations, and other customer offerings. It is not our intent to rely on any option reduction strategies for improvement. Thus, in this section we work with the existing variation to recommend measures that can be taken to improve operational effectiveness and bottom line margins while not reducing the variation. In the next section of this chapter we will discuss methods for reducing the variation we observe, but we have limited ourselves to only those recommendations that do not affect the current overall breadth of offerings to the customers.

Underlying all of the following recommendations is one common element: information sharing. The importance of sharing the results of these analyses and other like efforts cannot be underscored enough. The collective capabilities of the experienced Boeing workforce, from the management to the hourly workers, far surpass our abilities to draw appropriate conclusions from this data. While we are able to apply the latest theories and academic concepts to make sense of our findings, nothing that we do can equal the vast knowledge and problem-solving capabilities of those who are most closely involved with the processes. If there is one responsibility to convey it is the necessity to set up an appropriate environment which is guided by fundamental principles of the business and where all available resources and knowledge are at the disposal of those who can apply it best. All too often the fear of competitive espionage inhibits the channels of communication, when the cost of failing to communicate far outweighs that of the information falling into the wrong hands. Boeing is rife with incredible human talent and if it is to successfully regain its market-leading position it will have to find new ways to capitalize on that talent by clearly communicating its desired direction, arming its people with the necessary tools and incentives, and letting them lead the company forward.

A second overarching theme throughout this analysis is the importance of meaningful data collection. We present several strong arguments that there are significant differences in the cost of different airplanes, and this is based on the limited information that was actually obtainable. Based on the results of our analysis there is evidence to suggest that the additional collection of data on individual planes, specifically within engineering and component parts, is desirable. It is thus recommended that Boeing investigate on a limited scale, the potential of tracking cost for individual planes, beyond the areas it currently does.

4.1 Acknowledgement of the Variation

4.1.1 Factory Decisions

Initially, there were three operational areas that we believed could benefit from better information about the drivers of cost: Plane scheduling, workforce scheduling, and equipment and engineering investment decisions. Indeed, our findings confirm these results and offer two additional suggestions.

Currently, the Program Management Office (PMO) handles the process of scheduling planes. There is a list of criteria and methodology for determining the appropriate firing order. Originally we suspected that the number of planes between configurations might affect the cost of the plane in which case we could recommend strategic order of planes to minimize cost. However, the results of the data bore no indication that the gap between planes or configurations had any relevance to cost. Nor did the number of labor units of the previous aircraft. Thus, our first inclination was wrong. Nonetheless, the data suggests one strategy currently employed in the firing order decisions that will be aided by the results of our analysis. PMO's current practices try to schedule particularly difficult airplane at the beginning of the month because contractually Boeing only promises delivery of an airplane by month. The earlier in the month a plane is scheduled the more likely Boeing will be able to meet its contractual obligation. With this in mind and a more accurate ability to forecast the cost of a particular plane, *it would be worthwhile for Boeing to measure monthly on-time delivery performance and experiment with the scheduling of planes in descending order of difficulty over the course of the month.*

A second area where prior knowledge of expected cost could have a substantial effect on Boeing's operations is with workforce scheduling. While it is difficult to assess the magnitude of this problem, the inability to accurately predict labor units and consequently staff labor for a particular plane has long been the bane of Boeing interior shop management. As mentioned above, a new system for rating planes has recently been implemented. Its effectiveness must be compared to this model. The more effective measurement should be proliferated throughout the company. Consequently, *Boeing should continue to evaluate different mechanisms for estimating cost, use the best methods to schedule its hourly labor in the interior installation shop, and measure the benefits or detriments of each.*

The next area in which Boeing can make substantial improvements to it current practices is with the allocation of engineering and equipment expenses. With better information about the sources of variability in the manufacturing processes Boeing can make informed decisions on where to focus its resources. At the highest level, the analysis in this paper suggests that the interior installation shop is the part of the airplane manufacturing process that incurs the more volatility in terms of cost per plane. While the analysis has identified a number of factors that seem to lead to high variability, we also know that there are systemic reasons as well that contribute. Many of the problems occurring in the final assembly process manifest themselves at the end of the line. Thus, even without knowing the specific causes of this variation we can address the inevitable problems by building an assembly process that is more robust to swings in the labor units needed to build the plane.

Current Operational System

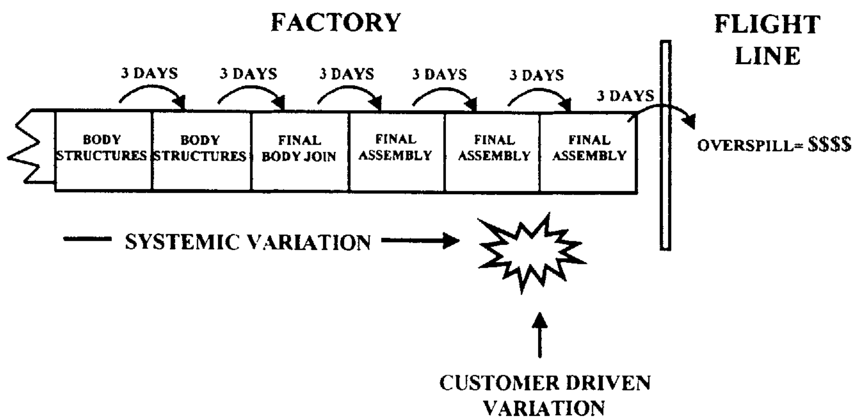


Figure 7- Variation manifests itself at the end of the factory processes.

Figure 7 shows the flow of the airplane assembly process and the location at the end of the line where the majority of the hourly variation occurs. In our initial trials of our regression model, the travelers variable (working spilling out of position) correlates very highly with the cost of the total airplane assembly[20]. We therefore suggest that any effort to reduce the number of travelers would substantially improve the overall assembly costs of the airplane. Our recommendation to eliminate the effects of the end of the line variation problems is based on applying some of the basic principles of queuing theory to the last stages of the assembly process in the factory. Currently, an airplane will spend a fixed period of time at each final assembly position regardless of the complexity of the configuration or the options chosen. In order to keep up with the flow each plane must be moved to the next position on a regular basis. Not only is a significant number of labor units used up in the move process, but there is also a substantial downtime from the work on the interiors installations and systems testing that results in a large interruption of work at a critical time in the process. To mitigate these effects *we suggest that a parallel assembly process be investigated for use in the final assembly area rather than a serial*

[20] We did not include travelers in our regression model because they represent a symptom of variation not a potential cause.

one. **Figure 8** shows how having three[21] parallel bays that are each equipped for the entire period of final assembly interiors, exteriors, and systems installation.

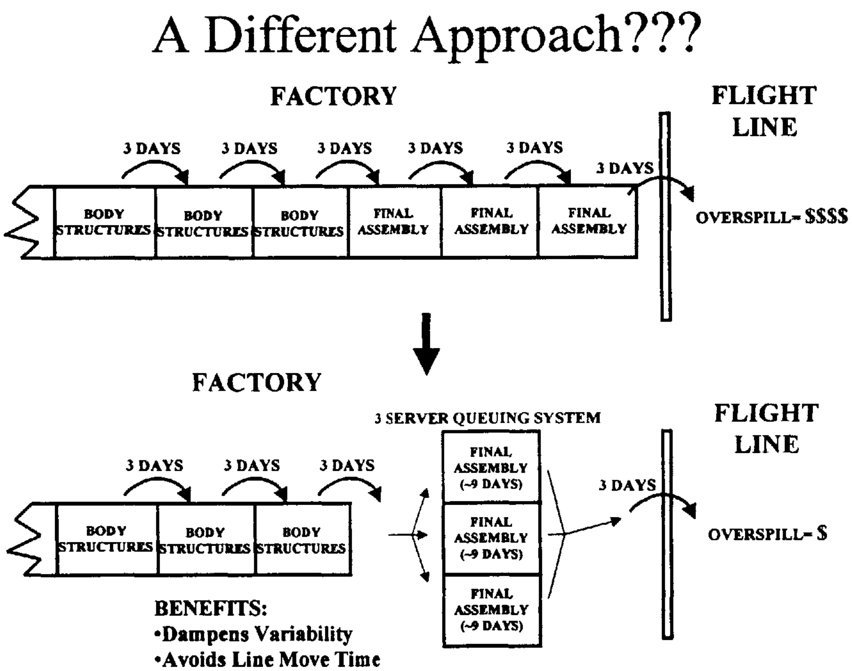


Figure 8- A suggested improvement to the current factory flow. Parallel shops dedicated to the final interior and systems installation would dampen many of the effects of variation.

Not only would parallel bays for final assembly eliminate two airplane moves, but more importantly the multiple locations would also dampen the costly effects of variation by reducing the amount of expected overspill out of the factory. While this suggestion might prove especially costly for current models that are already in production, we strongly recommend parallel shops for future models and their new lines. The principles of queuing theory are a particularly powerful means of addressing variation and could also be applied at lower levels of the manufacturing process as well. One particular type of response to high variation is investing in standard interfaces. Not only can Boeing invest in equipment for the process flow (i.e. parallel bays), but it can also work to invest in the product itself to facilitate the manufacturing process. Boeing is currently

[21] Three bays is the minimum number of assembly bays that would suffice. Four bays may be an appropriate number and further analysis would be needed to determine this based on the investment cost in each bay.

evaluating numerous potential projects to save costs, and to its credit many of these will be implemented, but to truly excel Boeing will need to find new ways of implementing these types of changes, perhaps by including manufacturing efficiency in its criteria for project selection.

While the aim of this paper has been to focus on the 777 model aircraft only, we have continually maintained that the adverse effects of variation seen on the 777 are only accentuated on the other models, especially the other twin-aisle aircraft. Given the nature of interior configurations to be highly independent of the model there is a unique opportunity for Boeing to make many of these investments across multiple platforms. Airlines themselves want fleet compatibility and uniformity in terms of their interior configurations and Boeing undoubtedly would like to amortize their development efforts for standardization or implementation facilitation across as many units as possible. Thus when evaluating cost savings decisions Boeing should be considering payback not only with the model for which they are developing the improvements, but also the transferability of that knowledge to other models. In this way the hurdle for undertaking manufacturability improvements will be lower. Naturally, there is an important consequence that the different airplane programs must increase their communication and knowledge sharing to make this investments pay off. Several initiatives were underway with this purpose during this project and they should continue to be encouraged.

In a fourth area of improvement, Boeing has long been aware that the late delivery of buyer furnished equipment has plagued its assembly process and escalated its manufacturing costs. Our analysis helps confirm this notion and reaffirms the importance of dealing with late buyer furnished equipment. Boeing has recently implemented a program that seeks to follow through on the terms of the purchase contracts will hold customers responsible for the late delivery of buyer furnished equipment. The preliminary results of this program seem exceedingly positive even though specific results were not available at the time this paper was written. While there are many different suppliers to deal with, the problem of late buyer furnished equipment is clearly containable and thus capable of being addressed. *Boeing should continue with its* *program of contract enforcement and continue to work with suppliers to ensure timely delivery of buyer furnished equipment in the future.*

A final operational area that has been isolated by our analysis is the impact of customer pickups and defects that have on the total costs of manufacturing. According to our interviews with Boeing's management team, different customers have different levels of scrutiny that they apply when accepting their aircraft. While some customers tend to be lenient with Boeing in forgiving minor defects. Customers willing to forgive minor defects (a smudge or a fractional misalignment in wallpaper) are not rewarded for their leniency, while customers who complain reap benefits while Boeing incurs additional costs. Instead, Boeing needs to reevaluate its customer inspection policies to more appropriately align customer incentives with those of Boeing. The data implies that an associated cost of each defect could be quantified and used to determine an appropriate customer policy. One way in which Boeing may be able to carry this out is to share some portion of a discretionary budget with those customers who take delivery upon more favorable terms. Obviously Boeing should not be able to deliver low quality planes, but at the same time they need to be more vigilant for egregious abuse of their system.

4.1.2 Selling Decisions

While the results of this analysis are valuable to the operational arms of Boeing's business, their full efficacy cannot be realized until they are incorporated into the other functions that complete the entire business model of selling commercial aircraft. Namely, Boeing's primary goal is to sell airplanes as profitably as they can and this is only possible if they have a complete understanding of the cost structure of what they are selling. Today, Boeing's sales force has a limited understanding of the costs associated with building an airplane. Their sales decisions, while focused on their customers, are lacking a critical element necessary to execute favorable outcomes to both players. *Any additional information on cost Boeing can incorporate into its sales decisions can only positively affect profitability and customer satisfaction.*

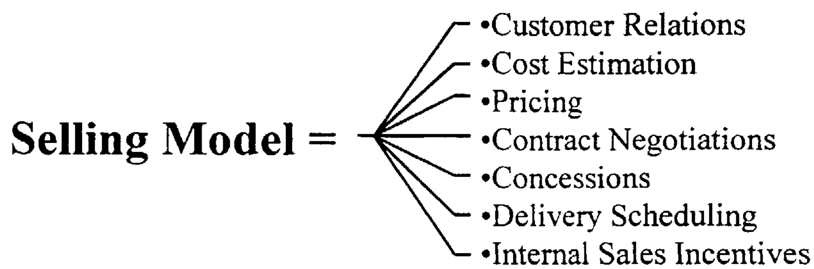


Figure 9- Components and factors involved with selling an aircraft.

More accurate information about the true costs of particular options and configurations on an individual aircraft can impact Boeing in several ways. The first and most obvious way in which better cost information improves Boeings business is that prices can be set more accurately to reflect not only the market preferences for particular configurations but also the appropriate costs of manufacturing. Not only will the costs be more fairly distributed among those customers who are asking for more expensive configurations and options, but also the customers will be steered to make better business decisions by selecting those options that benefit them the most economically. Better informed customer decisions in turn will help Boeing better understand its market and the popularity of its option and configuration offerings that in turn help Boeing make more informed financial decisions about which options and configurations to offer.

A corollary effect of better cost information in the sales process is the capability to *redesign the sales incentives to more accurately reflect the goals of the business.* For years Boeing has struggled to design an appropriate sales incentive plan for its sales force. With imperfect cost information a basic measure of profitability has been difficult to implement. If this analysis proves anything it is that there is considerable stability and predictability among Boeing's manufacturing processes. If this is the case then Boeing must begin to hold itself to a higher standard of information accuracy. They should carefully delineate the ownership of certain metrics and surround them with corresponding incentives that are aligned with their overarching goals for profitability. In this instance we proposed three distinct responsibilities of which different groups could begin took take ownership: estimation accuracy, cost reduction, and profitability. Since every plane is sold before it is built, Boeing's ability to estimate cost is of critical importance. If the sales group is going to appropriately price each sale of airplanes it must understand cost to if it wishes to maximize profit. It therefore must have as accurate an estimate of cost as possible as it enters into negotiations with a customer. Thus, if Boeing desires to maximize its profitability then it must design incentives for its sales force to do the same. The sales force, in turn, needs accurate cost information at its disposal. Since cost information is under the umbrella of operational ownership, operational groups should own the responsibility of ensuring an accurate estimate of cost. However, the operational group also needs to own the responsibility of continually lowering costs that could inherently conflict with its incentives to give an accurate estimate of cost (i.e. a higher than expected cost could be submitted to the sales and marketing organization to facilitate steady cost improvements. a.k.a. "sandbagging"). Thus, the operational group must be measured not only on how well it lowers its costs, but also on the absolute accuracy of its cost forecasts. Likewise, the sales group can be given incentives to maximize profitability based on the cost estimates given to them. The overarching purpose of this recommendation is to encourage Boeing to continue to *examine the importance of information accuracy and information sharing.* In order for Boeing to compete effectively it needs to engage all its business groups around common goals and clearly delineated responsibilities of each group so they can achieve those goals. By improving the accuracy of its most important data points, such as cost of an individual plane, Boeing is taking a large step in the right direction.

4.2 Variation Reduction

While it is our contention that enormous operational and profitable improvements can be made without altering the ultimate offering of options and configurations to the customer, we nonetheless recognize that new opportunities for cost savings will unfold that will require option or configuration reductions. However, with customers making more informed decisions about their needs because of more accurate pricing, and Boeing having a more thorough understanding of its profitability because of better costing methods, appropriate option reduction decisions will be made more easily because there is more compelling information to support them. Thus, there are really two primary ways to deal with the variation Boeing is experience in the interiors shop. The first way is to invest in engineering and equipment that minimizes the impact of having a broad portfolio of offerings. We address this in the section above by recommending investment in standard interfaces and other mechanisms that will facilitate manufacturing and assembly of the aircraft. The second method of reducing the variation is to reduce the breadth of offerings itself. As we have mentioned above, because of the highly contentious nature of this alternative, we recommend for Boeing to wait for overwhelming support across multiple organizations before taking this tack. However, we are also confident that the additional attention to data accuracy and the proliferation of cost information will make these types of decisions considerably easier for Boeing management to make.

Chapter 5: Conclusions

In this final chapter, we conclude by reiterating some of the common themes of this paper. Our most notable findings are that the installation of the interiors causes a significant portion of the variability in the cost of the planes. Furthermore, much of this variation is predictable because the origins of the variation in cost are parameters known at the time the plane is sold. There are numerous business functions throughout Boeing that can benefit from improved cost forecasting, and there is tremendous potential for additional profits from both decreased costs and better pricing to have a lasting and substantial impact on value Boeing creates for its shareholders. Also underlying all our recommendations is the importance Boeing must place on distributing information across its commercial aircraft organizations. The more clearly Boeing can define its goals and the more efficiently different areas within Boeing can come to a common understanding over what is going on, the more rapidly Boeing will be able to improve its operating practices. In the case of this study, the power of the results do not lie in any specific regression results, but instead in an aligned understanding of the drivers of the cost of an airplane and the overall effects that severe variation have on Boeing's business. It is our hope that Boeing will continue to invest in further studies that not only seek to refine this current model, but also work to increase the general understanding of the Boeing commercial business model among all internal constituencies.

5.1 Stability and Predictability in the Airplane Assembly Process

The results of our study conclusively demonstrate that the options and configurations of the interior section of the aircraft account for a significant portion of the overall variation in the airplane assembly process. Furthermore, despite notions to the contrary, we have also shown that there is, in fact, considerable stability to the airplane manufacturing process. Our regression analysis tells us that there is overwhelming evidence to support high predictability in the costs of each airplane based on factors that are known at the time the order for the plane is placed and long before the plane is manufactured. While Boeing will continually be required to deal with the inevitability of unforeseen events, we have identified several events that seem highly problematic and we recommend prescriptive measures that Boeing can take to mitigate their effects. At the same time, we also suggest other means for Boeing to accommodate the large swings in cost that naturally result from a broad product offering.

5.2 Importance of Communication and Information Sharing.

This analysis means nothing if widespread access is not given to its findings. Furthermore, in order for the findings to be understood, the context in which they are valid must be outlined. In other words Boeing must constantly be defining and reinforcing the goals of its business from two perspectives. First, the fundamental principles that underlie the commercial aircraft business must be clearly delineated among all the Boeing commercial aircraft divisions. Boeing must create a general awareness among its divisions about the roles each of the areas of the organization play in creating value for their customers and how each group contributes to the profitability of the company. Second, Boeing must establish a direction that is clearly understood across the company that provides guideline for improving Boeing's business model. Thus, it is not enough for the organizations within BCAG to understand where they are, but they must also understand where they are going. The Boeing workforce is an incredibly capable and competent body and needs to be recognized as the powerful asset that they are. With a little more knowledge about how they factor into the business model, their existing status, and their relative contribution as compared to other groups in the organization, the Boeing employees and junior management can contribute immensely to Boeing's success as a business in addition to being a technological leader. These steps above are accomplished only through communication and information sharing. Informed decision-making is required throughout the organization and across the ranks of management and engineering and knowledge about what is going on and where Boeing needs to go is a critical to enabling this to happen. At the highest level this analysis simply has taken readily available yet dispersed data from across multiple divisions, transformed the data into an easily comparable format, and pulled it together to tell a story about what is happening in the current production environment. If Boeing is to succeed it must do the same across all levels of its business.

5.3 Further Investigation is Necessary

Our final message, and hopefully our most convincing argument, is to relay the importance of further investigation into this matter. Boeing has long been troubled by the presence of variation in its manufacturing processes. and it should by now fully understand the magnitude of this problem and correspondingly the potential upside to the business if the problem can be solved. What we hope we have done with this paper is to have shed new light on this problem by providing evidence that there is considerable rationality and predictability to the overall cost of each airplane, and that better information about the individual cost of an airplane is a worthwhile pursuit.

Appendices

Appendix 1: A Summary of Boeing Financial Data (1997 to 1999)

(Dollars in millions)	Net earnings (loss)						Sales and other operating revenues					
Year ended December 31,	1999		1998		1997		1999		1998		1997	
Commercial Airplanes	**$2,016**	**49%**	($266)	-16%	($1,589)	-1458%	**$38,409**	**66%**	$36,880	64%	$27,479	59%
Military Aircraft and Missiles	**$1,193**	**29%**	$1,283	79%			**$12,220**	**21%**	$12,990	23%		
Space and Communications	**$415**	**10%**	$248	15%			**$6,831**	**12%**	$6,889	12%		
*Information, Space and Defense Systems**	*$1,608*	39%	*$1,531*	94%	*$1,317*	1208%	*$19,051*	33%	*$19,879*	35%	*$18,125*	39%
Customer and Commercial Financing/Other	$492	12%	$367	22%	$381	350%	$837	1%	$730	1%	$746	2%
Accounting Differences/eliminations	($432)	100%	$372	100%	($177)	100%	($304)	100%	($1,335)	100%	($550)	100%
Share-based plans	($209)		($153)		$99							
Other unallocated costs	($305)		($284)		($287)							
Earnings (loss) from operations	$3,170		$1,567		($256)							
Other income, principally interest	$585		$283		$428							
Interest and debt expense	($431)		($453)		($513)							
Earnings (loss) before taxes	$3,324		$1,397		($341)							
Income taxes (benefit)	$1,015		$277		($163)							
	$2,309		$1,120		($178)		**$57,993**		$56,154		$45,800	

*Prior to 1998 Military Aircraft and Missiles and Space and Communications segments were combined under one operating business unit

Source: 1999 Boeing Annual Report

Appendix 2: Model Variables

Dependent Variables

Labor Units	***Definition***
Total Factory Labor Units	The total number of Labor Units charged to the factory. This is the summation of the eleven shops that comprise the final assembly and installations of the aircraft. This does not included flight line testing labor units. Labor units is a generic term which reflects efforts proportional to the amount of time it takes to do something.
Interior Labor Units*	This is the total number of labor units charged to the interior installation shop (UF320). This includes all work done in the factory AND all work that was supposed to be completed by the shop yet subsequently traveled with the airplane onto the flight line.
Flight Line Labor Units	This is the total number of labor units charged to the aircraft for work done after the factory, excluding any work that was supposed to be completed by the factory.

Customer-Driven Independent Variables

Aircraft	***Definition***
Model	The major model of the 777 aircraft. There have been three major models of the 777 family to date: 777-200, 777-2ER (Extended Range 200), and 777-300
Footprint	This variable refers to the size of the aircraft. The 777-200 and 777-2ER have the same size fuselage and thus the same footprint. The 777-300 is considerably larger than the other models and thus has a different footprint. This variable was included because the interiors installation effort with respect to size does not differ between the 777-200 and 777-2ER.
777-200	Boeing's first 777 aircraft.
777-2ER	An extended range upgraded aircraft from the 777-200. The 777-2ER makes use of a central fuel tank to extend its range.
777-300*	Boeing's largest 777 aircraft. The 777 is considerably longer than the 200 and is recognizable by the extra set of doors over the wing.
Model Number	Every major model is assigned a unique number. This variable is for tracking purposes only.
Date Delivered	The planned delivery date of the aircraft. This variable is for tracking purposes only.
Factory Rate*	The frequency with which Boeing rolls a 777 out of the factory. At its peak rate Boeing completed a 777 every three days.
Learning and Memory	
Unit Number	The ordinal value assigned to each member of the 777 family of aircraft. The sample set of data for this project ranged over the first 234 planes built (excluding two planes). L/N 1 was never sold and is still owned by Boeing for engineering purposes, one other plane was sold confidentially without an interior.
ln(Unit Number)*	The natural logarithm of the Unit Number.
Footprint Order	An ordinal value assigned to each aircraft used to represent the sequence of that aircraft over all like footprints that were delivered. For example, L/N 43, the 2nd 777-2ER delivered, was the 42nd –200 footprint to be delivered. (L/N was never delivered).
ln(Footprint Order)	The natural logarithm of the Footprint Order
Model Order	An ordinal value assigned to each aircraft used to represent the sequence of that aircraft relative to all other like models. For example, L/N 43 was the 2nd 777-2ER to be delivered.

ln(Model Order)	The natural logarithm of the Model Order.
Configuration Order	An ordinal value assigned to each unique configuration to represent the order in which a particular configuration was delivered.
ln(Configuration Order)*	The natural logarithm of the Configuration Order.
Gap Since Last Configuration	The number of planes built since the aircraft last built with an identical configuration. A default value of 500 was given to every initial configuration (customer introduction).
ln(Gap Since Last Configuration)*	The natural logarithm of the Gap Since Last Configuration.
Gap Since Last Airline	The number of planes built since another plane was built for the same airline. A default value of 500 was given for the first aircraft that was delivered to a new customer.
ln(Gap Since Last Airline)*	The natural logarithm of the Gap Since Last Airline.
Customer	
Airline	The airline or leasing company that ordered the plane
Airline Binary (22)	These variables are binary identifiers of each of the 22 airlines. e.g., The United (UAL) Variable would be 1 for any United aircraft and 0 for any other aircraft.
Budget	A unique identifier assigned to each plane. This variable is used entirely for accounting and tracking purposes.
Code	A number from one to four used to account for the expected amount of engineering and other resources it will take to design and build a particular configuration. Code 1 refers to a customer introduction, or a first-of-a-kind configuration. Code 4 refers to a follow-on configuration. Codes 2 and 3 refer to configurations that have some significant change from a previous configuration, but are not entirely new.
Configuration	
Configuration	An identifying code assigned to each unique configuration. This variable is used for tracking purposes.
Flight Test*	A binary variable to identify aircraft used as flight test units to model introductions. These planes were eventually sold, but were initially built with mostly empty interiors. When they were sold the basic interior installation labor units were not billed to UF320 in the factory, but instead to Change Incorporation labor units.
ETOPS Rating	The ETOPS rating if the number of minutes away from an approved landing site the twin-engine aircraft can fly and still be in compliance with regulation.
Engines	The type of engines on the aircraft
Pratt	A binary variable denoting an aircraft with engines that were made by Pratt and Whitney. Pratt and Whitney built and sold several different engine models to 777 customers.
GE	A binary variable denoting an aircraft with engines that were made by General Electric. GE built and sold several different engine models to 777 customers.
Rolls	A binary variable denoting an aircraft with engines that were made by Rolls Royce. Rolls Royce built and sold several different engine models to 777 customers.
Classes	The number of planned classes of seats on the aircraft.
Classes Delivered	The number of classes of seats actually installed by Boeing
Total Passengers	Total number of passenger seats.
Premium Seats	Total number of highly customized first class seats. Premium seats are the most luxuries first class seats that serve as individual compartments for first class passengers.
Premium Seats Delivered*	Total number of premium seats delivered by Boeing.
First Class Seats	The number of first class seats planned for the particular configuration that Boeing will deliver with the aircraft.

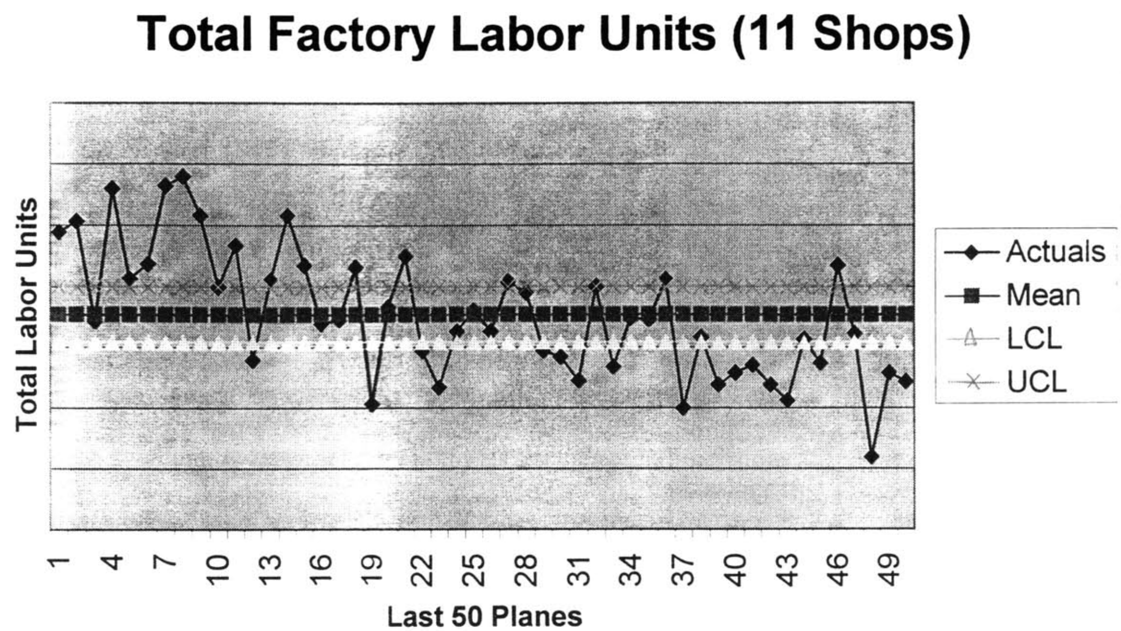
First Class Seats Delivered*	Total number of first class seats delivered by Boeing.
Business Class Seats	The number of business class seats planned for the particular configuration that Boeing will deliver with the aircraft.
Business Class Seats Delivered*	Total number of business class seats delivered by Boeing.
Economy Class Seats	The number of economy class seats planned for the particular configuration that Boeing will deliver with the aircraft.
Economy Class Seats Delivered	Total number of economy class seats delivered by Boeing.
First Class %	The percentage of first class seats out of all the total passenger seats.
Business Class %	The percentage of business class seats out of all the total passenger seats.
Economy Class %	The percentage of economy class seats out of all the total passenger seats.
First Class Pitch	The number of inches of stagger between first class seats. This is not the gap between the seats but rather the spacing of the seats between like points on the seats. For example the pitch refers to the distance between the front edge of one seat and the front edge of the next seat.
Business Class Pitch	The spacing between business class seats. This is not the gap between the seats but rather the spacing of the seats between like points on the seats. For example the pitch refers to the distance between the front edge of one seat and the front edge of the next seat.
Economy Class Pitch	The spacing between economy class seats. This is not the gap between the seats but rather the spacing of the seats between like points on the seats. For example the pitch refers to the distance between the front edge of one seat and the front edge of the next seat.
First-Business Divider	The number of inches from the front of the aircraft to the divider between the first and business class sections.
Business-Economy Divider	The number of inches from the front of the aircraft to the divider between the business and economy class sections.
First Galley Ratio	The number of square feet of galley space per first class passenger.
Business Galley Ratio	The number of square feet of galley space per business class passenger.
Economy Galley Ratio	The number of square feet of galley space per economy class passenger.
First Lavatory Ratio	The number of first class passengers per first class lavatory.
Business Lavatory Ratio	The number of business class passengers per business class lavatory.
Economy Lavatory Ratio	The number of economy class passengers per economy class lavatory.
First Closet Ratio	The number of inches of closet space per first class passenger.
Business Closet Ratio	The number of inches of closet space per business class passenger.
Economy Closet Ratio	The number of inches of closet space per economy class passenger.
Galleys	The total number of separate galley monuments.
Lavatories	The total number of lavatories
Closets	The total number of closets
Partitions	The total number of partitions
Partition and Closets	The sum of the number of partitions and closets (Small monuments)
Crew Rests	The number of crew rests planned for the initial configuration of the aircraft.
Crew Rests Delivered*	The number of crew rests installed by the interiors shop in the factory
VCC's and Purser Workstations	The number of Video Control Centers and purser workstations planned for the initial configuration of the aircraft.
VCC's and PWS's Delivered*	The number of Video Control Centers and purser workstations installed by the interiors shop in the factory.
Total Monuments	The total number of monuments (galleys, lavatories, closets, partitions, crew rests, VCC's and Purser Workstations) planned for the delivery configuration.
Seat Sections*	The number of distinct seating sections on the aircraft that are separated by a change in class, partition, or set of monuments.
Monument Blocked Sections	The number of seating sections on the aircraft that are entirely surrounded by large monuments such as galleys, lavatories, and closets.

Partition Blocked Sections	The number of seating sections on the aircraft that are entirely surrounded by small monuments such as partitions.
Oxygen Type	One of the two types of oxygen system options offered by Boeing. Canister oxygen containers are the most popular option for most customers. Several customers opt for gaseous oxygen system for use in planes that have routes over mountains regions and need greater oxygen supply.
Gaseous*	A binary variable that denotes an aircraft with a gaseous oxygen system.
Total Attendant Ratio	The number of passengers per attendant provided for by the configuration.
*Denotes selected model variables	

Systemic Independent Variables

Travelers	Travelers are the incomplete work that leaves with the aircraft when the aircraft leaves a given factory position.
Defects*	Similar to Customer Pickups that are problems identified by the customer, Defects are the total number of issues reported by the customer or customer representatives. One Customer Pick up could have several defects reported on it. While this in part represents the level of quality on Boeing's side, it also is somewhat indicative of the scrutiny with which the particular customer oversees its airplanes. The hypothesis here is that higher levels of scrutiny lead to higher cost airplanes.
Late BFE- Max Days Late*	This is the maximum days late any of the Buyer Furnished Equipment (BFE) are delivered to Boeing. Late BFE has historically plagued Boeing and caused considerable disruption to the manufacturing processes.
Master Changes	Master Changes (MC's) represent the number of engineering changes on a particular airplane. In the past these changes have been highly correlated to cost.
First Master Changes	This is the number of Master Changes that originated with the particular aircraft.
*Denotes selected model variables	

Appendix 3: Control Charts of Each Shop



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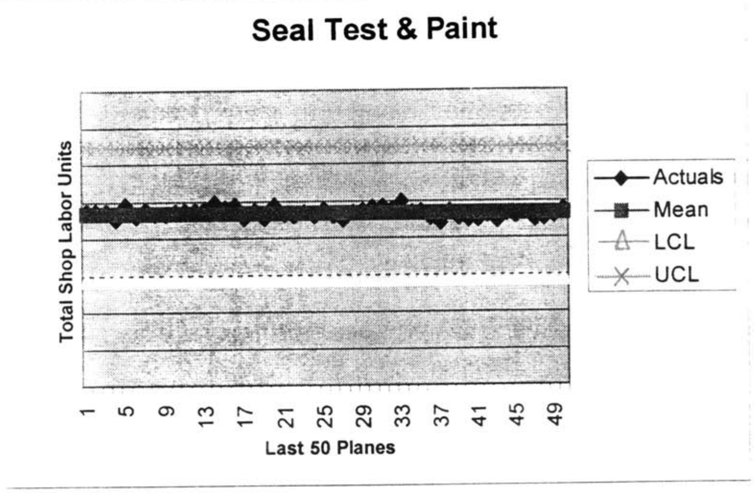

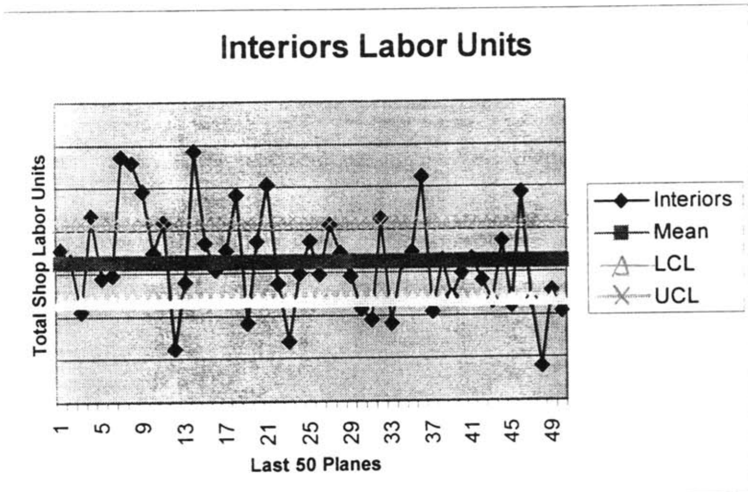

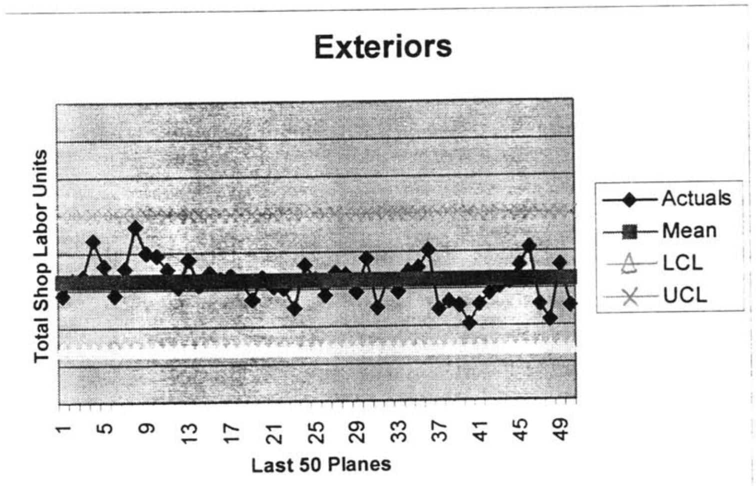

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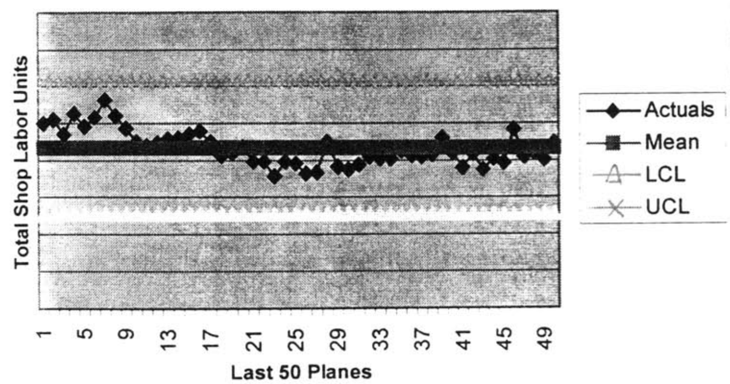
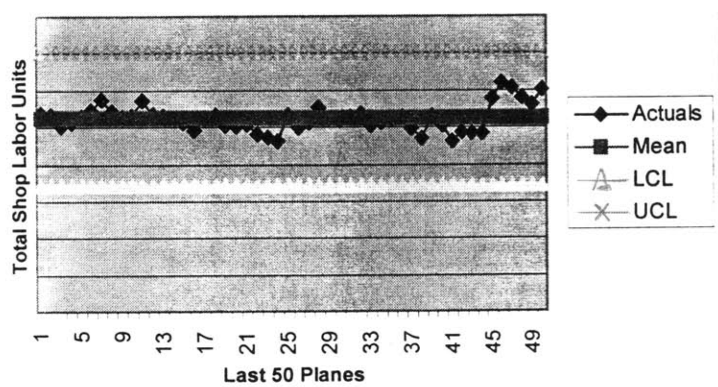
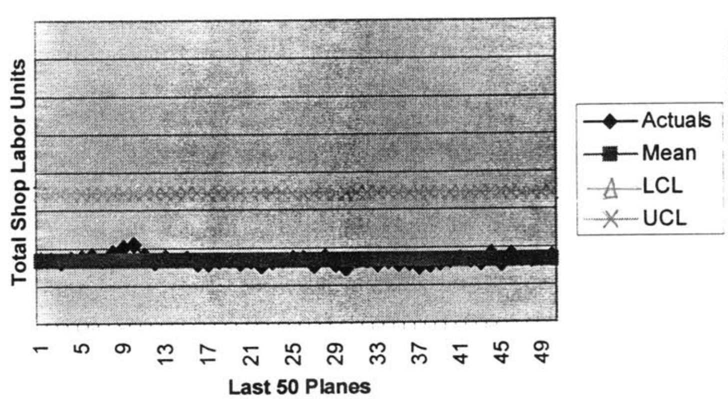
Systems and Doors



Systems and Doors



System and Doors



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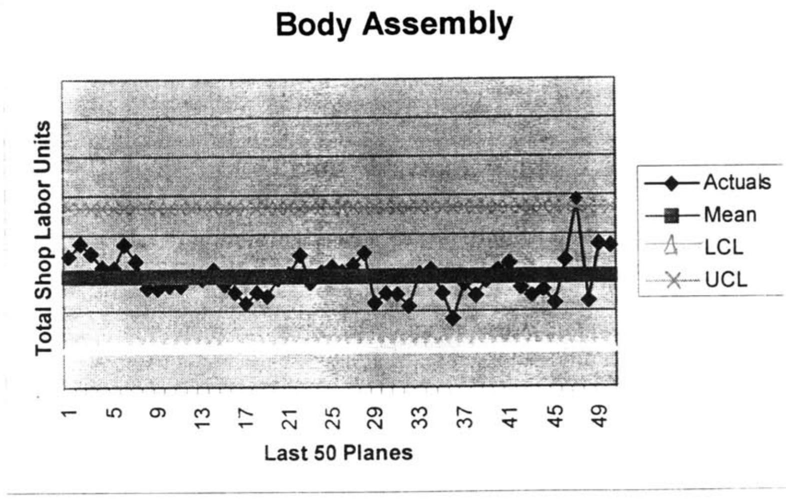

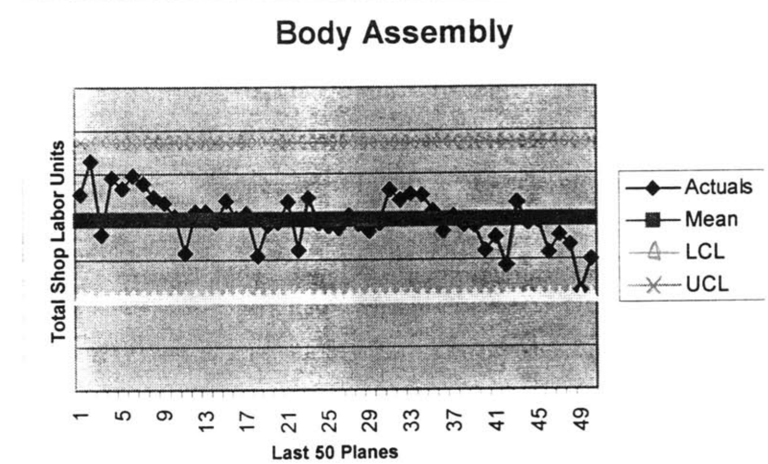

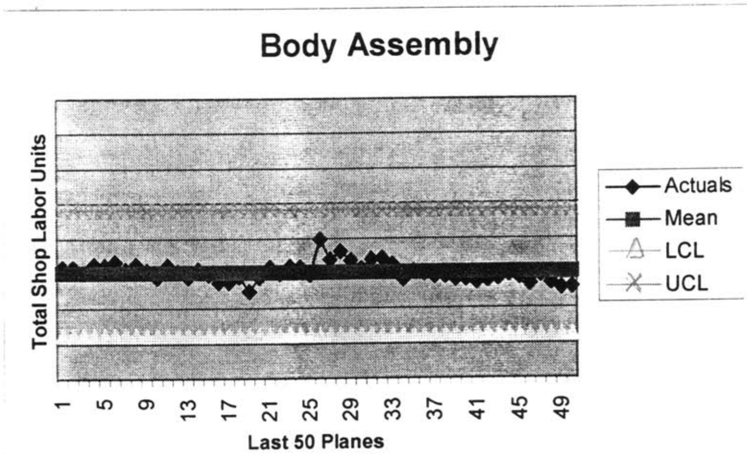

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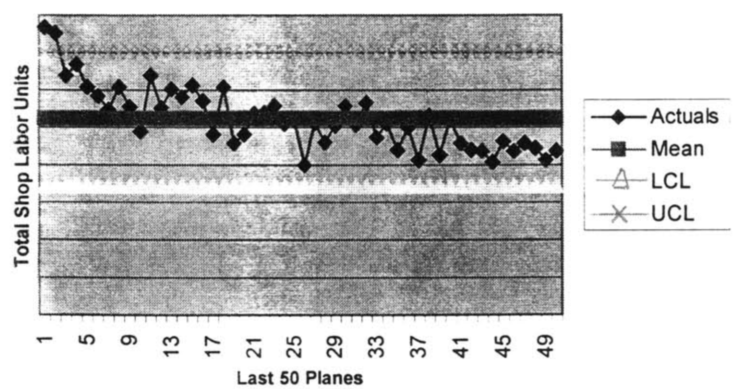
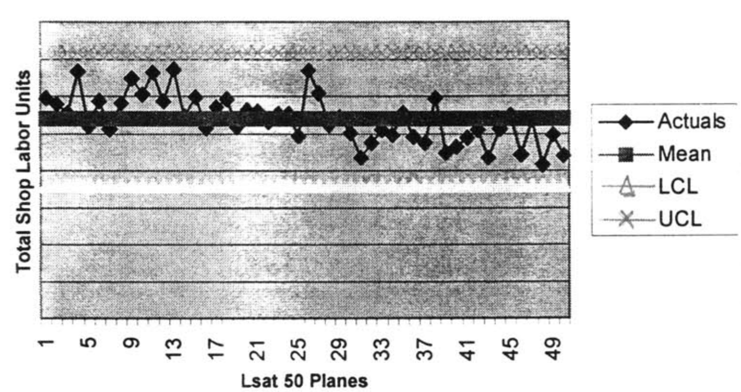
Wing-Body Join



Final Body Join



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