Assembly Process Development for Commercial Aircraft Using Computer-Aided Tolerance Analysis Tools

by

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

Master of Science in Management
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ABSTRACT

Design and production of large scale products provide many challenges in the area of integration and concurrent development. While computer-aided design (CAD) tools greatly facilitate the task of integrating the component design for an assembled product, few such tools are available to integrate the product design with the process design. Yet, the design of the assembly process, including the tool index scheme, assembly sequence, and component process selection strongly impact the quality of a complex product and the efficiency of production.

The purpose of this project was to propose new development tools that will truly integrate the factors of assembly with the product design. A design team's end goal of reaching a global optimum design of both product and process can be more easily accomplished using these tools.

The project focused on the Boeing Model 777 development process, which is currently entering production. Through a series of interviews with engineers and managers, the existing "Design Build Process" at Boeing was analyzed and findings summarized. Later, a production part was used to examine the possible impacts of assembly process design on product quality. The same part was analyzed using CAD three-dimensional solids modeling, which was the basis for a "paper prototype" of a new CAD tool for process development.

Findings

Based on the project investigation it was found that:

- The 777 development process provided an excellent environment for integrating the product, resulting in improvement at production.
- Assembly process design impacts the final product configuration through part-to-part and part-to-tool interactions.

- New CAD tools can simulate the behavior of assembly processes and predict the resulting product configuration.
- Decisions such as process selection, setting tool indices, and selecting an optimum assembly sequence can be made using these new tools.

Conclusions

The study showed that while the 777 development program at Boeing made huge strides toward concurrent product development, there is room for improvement in the area of process and product integration. A more integrated approach to product and process development is proposed, including the use of enabling CAD-based development tools, the change to an integrated scheduling environment at the level of design interface information requirements, and the application of an evolutionary design freeze concept.

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- Jim Byron and the members of the New Large Airplane Development organization who invited me into their midst to truly understand the complexity of our products; and
- My family and friends who have supported me during the past two years, particularly my parents and Janet.

Finally, I would like to dedicate this document to the memory of David Hall, a good friend and colleague from the Renton Division, who passed away in March. His support, guidance, and feedback helped me tremendously on this project, but his friendship and stimulating conversation are what I will miss the most.

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1. Introduction

1.1 Statement of Problem

From a manufacturing perspective, design integration is one of the most critical steps in the product development process. Left uncorrected, design integration errors can lead to interferences and gaps in the product at the time of production. Rework and replacement are often required to bring the product up to product standards. This circumstance is a fact of life for the mechanics of the airplane factories of Boeing Commercial Airplane Group. While the final product is of high quality, the process needed to assemble the airplane is far from perfect.

On Boeing's newest development project, the model 777, computer-aided design (CAD) tools have greatly facilitated the task of integrating the design of component structures and systems that make up an airplane. However, few such tools are available to help integrate the product design with the design for the assembly process. Yet, the design of the assembly process, including the tool index scheme, assembly sequence, and variation inherent in component fabrication and product assembly impact the final configuration of an assembled product tremendously.

Development of products in a "concurrent" fashion is the rage in many companies; that is, designing different portions of the product and process at the same time. Integration involves "putting together" the portions of the design to ensure that the product functions well as a whole. Process design determines how the product will be put together during the integration stage.

In order to move toward integrated concurrent product and process development, a new set of enabling tools are needed to analyze designs beyond the nominal state. In other words, the developers of product and process must consider the reality of variation in the manufacturing process.

Boeing is currently utlizing a "concurrent" product development environment on its 777 airplane. Also featured for the first time are computer-aided design tools and organizational changes which have helped bring functional disciplines closer together under one vision. This document outlines the learning gained during a seven-month research period within the 777 Division of the Boeing Commercial Airplane Group (Renton, Washington).

1.2 Boeing Background

Few other industries risk so much when a new product is launched, designed, and built. Boeing was built by executives who took "risk the company" approaches to expanding both the business and the product line. Today's competitive environment continues to require this "controlled risk" approach to product development. However, competition from Airbus Industries (based in Toulouse, France) has pushed Boeing to fill in holes in the range of products, redesign older models, and to protect the top end of the airplane market, the model 747.

Designing and producing a new airplane in the current competitive environment provides the company with some large strategic and logistical challenges including:

- **Investments in development costs for new aircraft are tremendous.** These investments are sky-rocketing just as the sophistication and complexity of airplanes are increasing. It has been estimated that the cost of the 777 development was $4-6 Billion, while estimates for developing a superjumbo have reached $30 Billion.[1] Boeing

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[1] Banks, Howard, "The Thin Line", *Forbes*, October 12, 1992.

must find ways to reduce the cost of developing and building new airplanes in order to fill gaps in its family.

- **The huge investments involved with new airplane development call for new strategies regarding business alliances.** Partnering with global aerospace companies could provide many opportunities, but also bring with it logistical issues of producing large sections of the airplane elsewhere in the world. Technology transfer between the partners is another issue. Learning must take place in both directions if Boeing is to stay in the leader's position in aircraft manufacturing.

- **Manufacturing is a competitive weapon to be utilized in the global marketplace.** Boeing's size and experience in manufacturing can be transformed into a competitive weapon with continuous improvement in quality and cycle time. Linking (more completely) the design of product and process for new airplane designs is an ideal way to begin exploiting company strengths.

- **Boeing must cut the time for new airplane development.** Manufacturers who can bring new enhanced models to market faster will have the competitive advantage over slower firms. While not taking shortcuts in design, the company must find ways to reduce the time from concept to delivery. By improving the integration between the product and process designs, thus improving product quality, would allow drastic reductions in the production times required for the first models (in a sense, moving down the learning curve while still in development).

1.3 Boeing Design Build Task - Scale and Scope

The concept of bringing together millions of component parts, miles of wire, and hundreds of subsystems to produce an airtight vehicle made to fly is mind-boggling even to those in the aerospace business.

On almost every scale of complexity, airplane design is the most complex. Below is a deomonstration of this complexity, comparing three "complex" products, the Model 757-200 airplane (an average to small sized airplane), an automobile from a auto maker, and an engine for a luxury automobile from a second domestic auto maker:

Order of Magnitude Comparison of Complex Products

	Model 757-200	Automobile	Automobile Engine
Total Number of Component Parts	1,000,000	50,000	350
Number of Unique Component Designs	100,000	10,000	300
Total Number of Engineers	4,000	1,000	30

Estimates based on company information and company representatives.

With this great complexity comes many challenges. Communication between engineers, integration of design, and control of the manufacturing process become the greatest concerns for airplane developers. In the end, the performance of the airplane is critical, no matter how many parts must come together.

The 777 program has made great improvements in aircraft development by improving the ability of engineers to communicate, and to integrate product designs using the computer. As discussed later in this thesis, integration and communication surrounding the design of the process is the next stage of improvement.

1.4 Historical Approach to Product and Process Development

In order to understand the context in which the product and process development of an airplane takes place, it is important to understand the history that shaped the design and production activity at The Boeing Company. Specifically, I will discuss the company's past practices in the areas of:

- Design engineering versus manufacturing;
- Design integration (use of a production prototype); and
- Tooling philosophy for assembly.

Design Engineering versus Manufacturing

Frequent communication between engineers who design the product and engineers who design the process is an essential element in the development of a new product. Although cross-functional communication and team-work is now standard procedure on Boeing's newest program, the Model 777, this was seldom the case until the mid-1980s. The traditional serial model of design was strictly enforced. As one manager on a missile program of the 1950s explained it, "the engineers lived up on the fourth and fifth floors of Plant Two while the Manufacturing people were on the first two floors. Engineers would literally throw drawings down a chute, saying 'Here make this'."[2]

This adversarial relationship between engineering and manufacturing is slowly eroding in the company. However, many decision processes and organizational charters still linger from this period of time.

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[2] Serling, Robert J., *Legend & Legacy: The Story of Boeing and its People* , St. Martin's Press, New York, 1992, pg. 165.

Design Integration

Boeing's leadership in the commercial aircraft business can be partially attributed to the company's competency in the area of system integration. Bringing together an airplane is difficult due to its complexity and shear volume of components. Integrating a design that allows the production of some models as fast as one per day is remarkable.

Before computers, the primary tool for designers to integrate product designs was the production prototype vehicle; or as Boeing calls it, the Mock-up vehicle. This prototype of the entire airplane (often in pieces in order to fit in existing space) was the last chance to test the design prior to the assembly line. In many cases, the actual detailed design layout of systems (such as tubes or wiring) was completed in the "Mock-up". Often, the factory floor itself was the final stage for re-configuring systems. Even after years of production of a particular model, a team of mechanics from the mock-up shop may rush to the factory floor to re-configure a system layout in an attempt to solve design integration problems on older airplane models. This approach to design integration is extremely expensive, because of rework, scrap, and required special skills institutionalized within the process.

Despite these obstacles, however, the Boeing approach to system integration of the airplane works. The mock-up is still a part of the psyche of the company, particularly for production people. Few managers in manufacturing were instant converts to the concept of digital mock-ups; possibly with good reason. There still is no disciplined process to account for the variation inherent in the assembly process. However, computer-aided design tools have changed the relationship between engineering design and production entirely.

Tooling Philosophy

Historically, the reigning philosophy of the tooling experts within the Boeing Company has had a profound effect regarding the approach used for production of the airplane. As with manufacturing itself (as is described by J. Jaikumar in his study of Beretta of Italy[3]), the philosophy that establishes the function of assembly tooling has slowly evolved with each succeeding airplane model.

The initial ideas about tooling for mass production of airplanes originated at Boeing with a group of tool designers from the automobile industry who were brought into the company during the early days of World War II. Within three years time, Boeing moved from a producer of no more than 35 airplanes in a given year to producing one new B-17 bomber every 49 minutes.[4] Much of the success found during this drive can be attributed to the tooling concepts.

Tooling philosophy in the aircraft industry is defined as the concepts used to establish location and integration of component parts and assemblies of an airplane in order to maintain the designed configuration and shape for the airplane. Appendix I describes the evolution from gauge-centered tooling concepts of the first commercial jet transports to the new data-centered approaches to be used on the next generation of products. This history still impacts the design of airplanes. The mental models of managers and engineers regarding the best way to design products and processes depend directly on the designer's understanding of the tooling philosophy.

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[3] Jaikumar, J., *Beretta*, Harvard Business School case study 9-687-044, revised 2/89.

[4] Serling, Robert J., *Legend & Legacy: The Story of Boeing and its People* , St. Martin's Press, New York, 1992, pgs. 56-57.

1.5 Research Plan / Project Scope

Research done for this project was completed during the Summer and Fall of 1992 in Renton and Everett, Washington. The primary focus of the research was the 777 program, which is moving into the final stages of design at the time of this writing. Also, Boeing's newest airplane development project, the 747X, was studied to some degree to see how lessons learned from the 777 had been integrated into the new organization.

Interviews and discussions were the primary vehicle of data collection for the project. These discussions were conducted with chief project engineers from different disciplines, top management from the area of manufacturing, engineering personnel intimately involved in the 777 product and process design, and design build team leaders from engineering and manufacturing.

Early on it became apparent that the area in which I could make the most contribution was the use of computer-aided design (CAD) as enabling technology to integrate product and process development. An example assembly was selected in the Renton Division to show the promise of new assembly process development tools.

The internship project and this thesis concentrate on the development of new airplane products, rather than derivative models or customer-specific design activity. However, I believe the concepts and techniques discussed in this paper can be applied to many other development tasks which involve the assembly of complex products.

1.6 Thesis Structure

This document begins by providing a general evaluation of the 777 program from the eyes of a semi-outsider to the Company. Building on the general structure created as part of the 777, the thesis goes on to evaluate the current literature regarding models for concurrent development. Next, I propose a new model for integrated, concurrent product and process development. Finally, I describe in detail a set of CAD-based development tools for the design of assembly processes that I believe should be the cornerstone of efforts to further integrate the design of products and processes.

2. Overview of the 777 Design/Build Process

2.1 Evolution of an Airplane Program

Since its conceptual beginnings in 1986, the 777 was going to be a different airplane program. It was destined to be the first time that Boeing took leaps toward improving the traditional process of designing and building a brand new airplane. For the first time, design and build were being considered simultaneously. With this fresh approach toward design, the program went forward to develop a new process for designing products and processes.

Market - Driven Development

One of the primary goals of the Company with this airplane was to *truly* listen to the customer and incorporate requirements, as well as suggestions, into the product design. The need to be customer-driven was manifested by a stated goal of producing a "market-driven airplane."

Boeing had always maintained that the customer was king, but some past programs failed to capture the essence of customer needs. Rather, many customers complained of a "we know what you need" attitude at Boeing, possibly dating from the days when Boeing did own and operate an airline.[1]

The design of the 777 program was different. Airline representatives were brought into the design process early in order to accommodate their requirements. For instance, during the conceptual stages of the airplane, several key potential customers from around the world were brought together to try to build a consensus of what the airplane should become.

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[1] Sterling, Robert J., *Legend and Legacy: The Story of Boeing and Its People,* St. Martin's Press, New York, 1992 pg. 16.

Meetings of this kind impacted the conceptual design of the airplane tremendously. Early concepts were discussed that would have stretched the existing structure of the Model 767, thus the early moniker of the program 767X. After consultation with the lead customer group, it became clear that the market need was driving the design towards a larger airplane. As a result, the 777 has a larger fuselage than the 767, more capacity, and comparable range. The customer group helped define the market niche the 777 should be targeting.

Customer input did not stop at the concept stage for the airplane. Airlines that had purchased the airplane were invited to become a part of the development process.[2] While not all accepted the invitation, United Air Lines and British Airlines, in particular, took advantage of the opportunity. Customer representatives were allowed to participate in management meetings where design teams (DBTs) presented their designs at various stages of development (called the integration DBT).

Increased involvement of the customer added tremendous benefits to both Boeing and the airlines involved in the process. However, direct customer input added a level of complexity to the design process which had not been experienced in previous programs.

Partnering

For the first time on an airplane program, the 777 program involved the resources of strategic partners. Japan Aircraft Industry (JAI) -- an alliance between Kawasaki Heavy Industries, Mitsubishi Heavy Industries, and Fuji Heavy Industries plus a few other Japanese aerospace manufacturers--took a

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[2] Firm orders from airlines for a new airplane are required before design and production can proceed.

21 percent share in the 777 program. In addition, development costs for the airplane were divided in the same proportion. Major portions of the fuselage and wing center section will be partially designed and built in Japan.[3] This arrangement provided Boeing with its first "partner" on a new airplane program.

While Boeing's supplier base has long been global, the addition of a partner in the development of the airplane added complications to the 777 development process. Issues of design integration, scheduling, and technology transfer are being addressed by the company and JAI. Since future airplane programs will likely feature these kinds of partnering situations, the ability of the company to learn from the 777 experience is critical.

2.2 Strategic Thrusts

Several initiatives, goals, objectives, and business strategies emanating from the upper management of the program, governed the development of the 777 design process. Strategic initiatives undertaken to differentiate the program from past Boeing airplane programs included:

- **100% Digital Product Definition**

  The design of the entire airplane was completed in three dimensions using a computer-aided design and manufacturing system (CAD/CAM). Boeing chose to use the CATIA™(Computer-Aided Three-Dimensional Interactive Application) developed by Dassault Systemes of France. Further more, the definition of assembly tooling was to be accomplished digitally.

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[3] Masterson, Joe, *Wing Newsletter*, February 20, 1991.

- **Three-Dimensional Solid Digital Preassembly**

Boeing utilized the ability of the CATIA™ system to compare relative locations of two or more designed components or assemblies to detect possible interferences. Designers were asked to share their models "early and often" in order to allow as much integration of designs from different disciplines as possible.

- **Concurrent Product Definition**

A disciplined design management system was used in order (quoting Boeing documents) "[to provide for] the integrated, simultaneous design of products and their related processes, including engineering, manufacturing, and support."[4]

- **Co-located Design Build Teams (DBTs)**

In an attempt to accomplish the simultaneous approach to design, a loose organization structure was established that utilized cross-functional teams for developing specific portions of the airplane.

- **Hardware Variability Control (HVC)**

Controlling the processes for the manufacture of the airplane became a high priority for the 777 Design team. To determine which attributes of components "mattered" to mating parts and product functionality, a number of "key characteristics" were identified for many component parts and assemblies. A top-down analysis technique allowed identification of key interfaces at each level of the assembly parts tree. The HVC approach also involved the inclusion of measurement capability within each assembly tool to get the measurement data

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[4] "777 Concurrent Product Definition Preferred Process Handbook", Boeing, 1991, pg. 6

required, and the limited use of statistical process control to monitor processes.

Although there were several other initiatives and objectives established for the program, these five strategic thrusts were most closely identified with the 777 and defined the actions of all program personnel. Below is a discussion of each of these initiatives, how they were implemented within the program, and a general analysis of their effectiveness.

2.3 100% Digital Product Definition

No other single decision within the 777 airplane development program had as much impact, or as much risk, as did the decision to design the airplane in a fully digital environment. Although Boeing had gained knowledge of the digital design process in the last few years during programs such as the B-2 wing design, no previous program had come close to the complexity and shear data volume necessary to design the 777 entirely on the computer.

In making this decision, there were many potential benefits for the company to digitally design the airplane:

- Accuracy of design data and easy coordination between mating designs;
- Use of the digital data by downstream organizations for fabrication and assembly;
- Integration of design within the computer rather than using physical prototype vehicles (so called "mock-ups") to determine fit between subsystems and substructure designs; and

- Accessibility of a single, common data source for design data that encourages teamwork and concurrency of design.

The increased cost of digital design were certainly recognized, but the highest levels of Boeing management decided to take this technology leap in order to improve the design process.

The strategy was implemented using the CATIA™ design system. Boeing had used CATIA™ for many years as its single, authorized CAD/CAM system. As the largest user of the system in the world (installed base)[5], many changes and improvements were made in order to accommodate the Boeing design process. At the peak of the 777 program, over 4,000 design engineers were involved in the design of the airplane and supporting systems. The design of assembly tools was also accomplished using the CATIA™ system.

The magnitude of the computing task of holding, accessing, and manipulating the enormous number of design files necessary for the design was a challenge. System response was always a concern, but had improved dramatically since the installation of CATIA™. The graphics system, alone, takes the power of eight IBM mainframe computers[6].

The design effort by the design engineers necessary to accomplish a digital design was underestimated. As one computing manager for the 777 program explained, "Designers had to actually redesign three times, first in wire frame environment, then in the three-dimensional solids environment, and finally to get a two-dimensional view for a released drawing."

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[5] Fiderio, Janet, "Electronic Teamwork Keeps Boeing Growing",*Computerworld Premier 100,* September 30, 1991.
[6] *Ibid.*

Another issue surfaced during the implementation of the digital strategy: the skill base of the users on CAD/CAM systems, and CATIA™ in particular, was lower than estimated early in the program. This concern was especially true for product design using three-dimensional solids modeling (the preferred mode of design). In the long run, the use of solids modeling has proven to be superior for accuracy and simplicity versus wire frame CAD construction techniques. However, the steps for designers to follow to accomplish a design using this technique were more a succession of shortcuts and tricks rather than a systematic approach.

Further complications arose when the solids designs were to be transformed into two-dimensional views or wire frames. Inaccuracies from the transformation often required the designers to change original solids model to be consistent. Since it is difficult to change a solid model after the initial design, recreating the model was often the only solution. The resulting reduction in design productivity was a universal problem on the 777 Program. At the present time, Dassault is working with Boeing to enhance CATIA™ in order to eliminate this problem.

How important was the use of the digital medium for this airplane? As a manager from manufacturing stated, "CATIA™ digital design was an essential vehicle of the concurrent engineering process." He went on to explain that the downstream uses of the digital data (i.e. digital pre-assembly and visualization) were of particular benefit, especially for the people in the operations organization who were able to see and understand the design of the airplane more clearly.

However, the problems of this experiment should not be overlooked. It took much longer to learn how to efficiently design production parts than most people had anticipated. Many managers at Boeing believe that the difficulty with CATIA™ itself was primarily responsible for the problems. A more objective view is that the company had a huge obstacle to overcome to complete design using a CAD/CAM system of any kind. Even if CATIA™ had been extremely user-friendly it probably could not have sped the transition of even the most experienced design engineers into the age of the computer.

The good news is that Boeing now has an established base of CATIA-literate design, manufacturing, and tooling engineers, which will make the next large airplane project much less painful. In retrospect, the agony suffered during the 777 digital design effort could well be one of the better investments the company has ever made.

2.4 Three-Dimensional Solid Digital Preassembly

Dubbed digital preassembly (DPA), the process of superimposing several computer models (three-dimensional solid designs) onto the same reference coordinate system provides information never before obtained prior to production. Data provided by DPA can show how the structure and subsystem designs fit together in the nominal state. Historically, the only source of integration information of this kind was in the Mock-up production prototype discussed in Chapter 1. In addition, the DPA process became the central figure in the 777 Program's efforts to concurrently design the airplane. It was found that there is no better way to integrate the designers than to force the integration of the product design itself. The "Mock-up vehicle" was now located within the computer.

Digital mockups enabled the 777 designers to gain feedback about designs and potential interferences much earlier in the airplane program than previously possible. Using a process of design integration and feedback defined at the outset of the program through the multi-disciplined design build teams, the DPAs provided information to designers and downstream users of the design.

Limitations of the CATIA™ software almost derailed the efforts to utilize digital data to perform DPAs. Boeing eventually developed proprietary software that enables the identification and retrieval of the design models by each section of the airplane. Using this software, all models that belong in a certain zone of the airplane are identified so that they can be included in the DPA. Once identified, a zone management[7] engineer can overlay all applicable models in CATIA™ to determine if there are interferences.

Although the computer is a tool in the DPA process, success of the procedure, depends to a large degree on good discipline by the engineers . The proprietary software tells the engineer what models impact or penetrate a specific area, but it is up to the engineer to "clash" (superimpose several solid models) the datasets involved using the CATIA™-based interference function. This is done by overlaying each model and checking relative locations within the composite model.

Due to the large amount of data included in these models, the process is limited to only 20 models at a time[8]. Therefore, the DPA process of checking all models impacting a zone of an airplane is dependent on a manual method of checking all combinations of models. Most zone managers use a matrix type system to ensure that all combinations are attempted. In general, a DPA occurred only at prescribed stage reviews, according to the overall program

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[7] There have been many debates about the best way to manage the integration process. At this point, there is a need for an engineer(s) who has the responsibility to put together all the designs for the entire zone.

[8] Based on CATIA™ training at The Boeing Company, June 1992.

schedule. However, teams were free to use the process at any point in the design process.

Future developments in graphics visualization and file management will provide a much more coherent approach to digital preassembly. The lack of a robust process for interference checking has contributed to several missed interferences during past DPA experiments. The same could hold for the 777. However, DPA has already detected a tremendous number of problems emanating from the integration of the design which would have been first discovered on the production floor in past airplane programs.

Even with the use of DPA and the increased degree of product integration, some felt that it had not gone far enough. As one manger from the electrical group stated,

> "Wiring is about the 'tail of the dog' in the design process. All wiring on the airplane is installed by these engineers. They are dependent on all the other disciplines for system locations, space allocation, schematics etc. Until this information is solidified, it is difficult to effectively solidify the wire installation design. The process should ensure that designs are shared between designers, and others, early and often. Designers shouldn't just keep refining their design without input from others. Each design impacts too many other people."[9]

2.5 Concurrent Product Definition (CPD)

Past airplane programs utilized a traditional serial model for the development of airplane design, tool design, manufacturing plans, and numerical control (NC) programming. From the beginning, the 777 program was to be different. A process was put in place that forced the concurrent development of design, tools and plans. In order to succeed, the process required a team environment characterized by the design build team, digital

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[9] Personal communication with a manager in 777 Engineering, July 15, 1992.

data and the ability to share data "early and often", plus the existence of an integrated schedule of the activities of a team.

A series of product definition stages were defined for the life of the development program. Each stage corresponded to a certain level of completeness of the design. Review of all designs took place at the end of each stage, requiring the "freeze" of the design in its latest configuration. Stage gates were established to ensure that every function had completed their required aspects of the design. These "stage exit requirements" were established by the design build team responsible for the substructure or subsystem. The stages served to force the integration of the product design.

One critique of the CPD process is that it did not facilitate the integration and concurrency of design in between the design gates. The goal of sharing digital design data early and often was not a reality. As seen in Figure 2.1, the number of CATIA™ models shared (used by second parties to evaluate integration or understand design concepts) spikes just prior to each stage design freeze. A more ideal situation would be to share design information uniformly throughout the stage period, with the final days devoted to design clean-up with *less* sharing. Figure 2.2 shows schematically the "gated integration" characteristic of the 777 concurrent product definition process as the design of the product progressively becomes more defined.

2.6 Co-located Design Build Teams (DBTs)

Design build teams were developed to increase communication between various functional groups, which wasn't evident in the traditional organizational structure. As discussed in Chapter 1, the design of an airplane is a compromise of many competing requirements and forces; therefore, the more communication between the various determiners of the design the

Figure 2.1

DPA MODELS SHARED AND PROCESSED

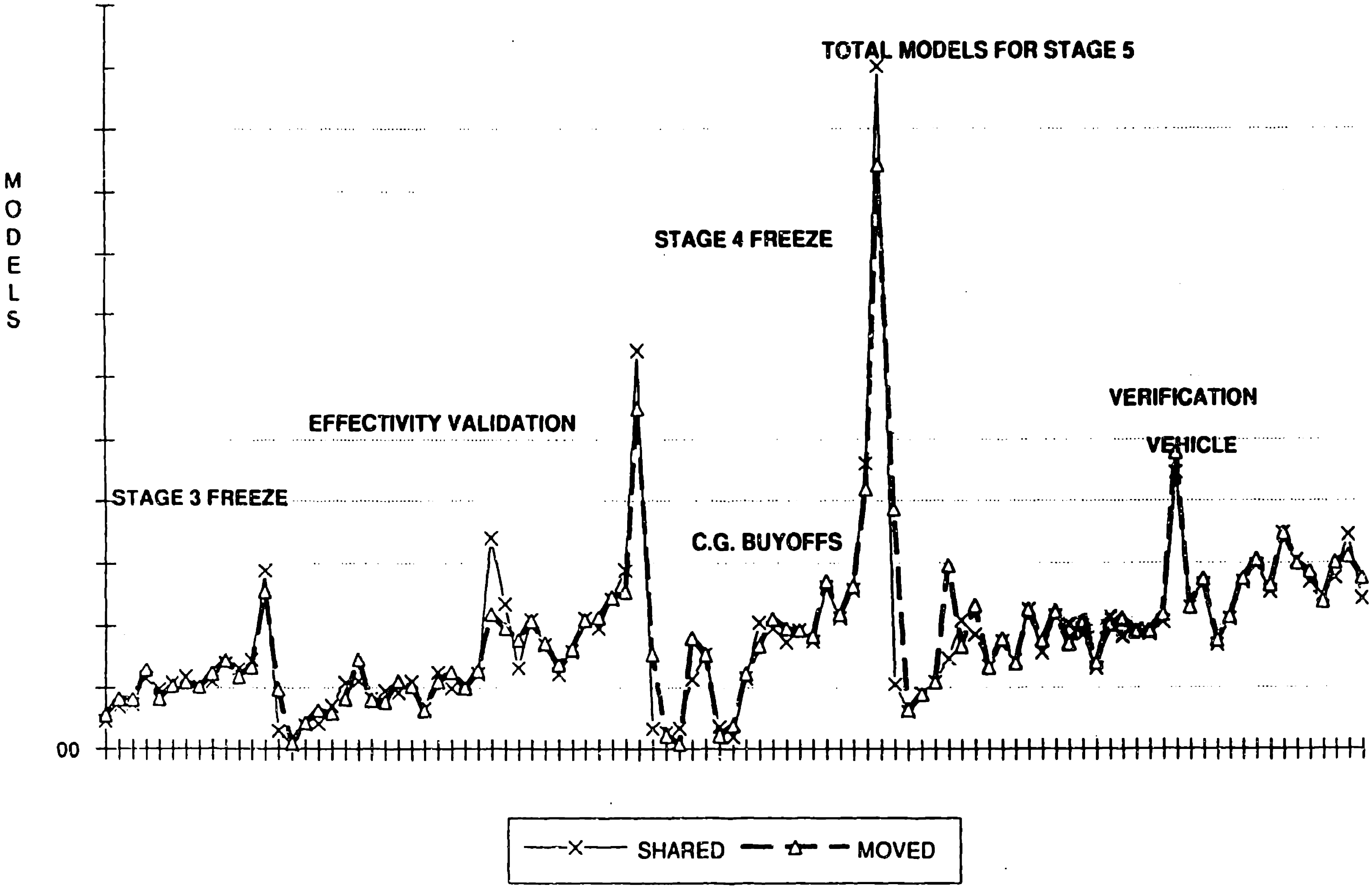
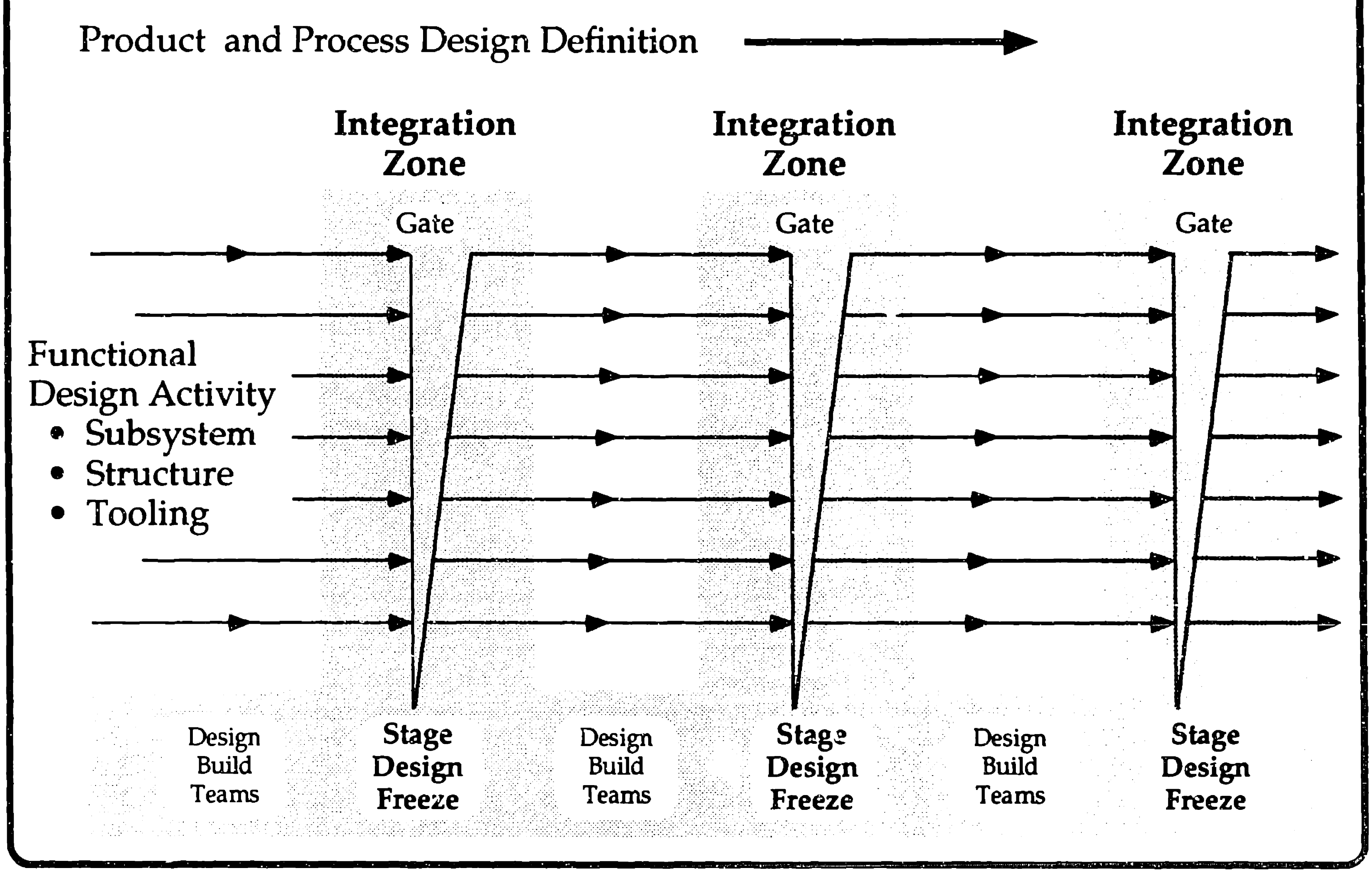


Figure 2.2

Current 777 "Gated" Design Definition Process



better. DBTs provide a formal mechanism for all involved in the product to exchange views and mutually define the direction for the design.

Boeing's decision to utilize DBTs was also based on the fact that the basic organization structure used for decades has not changed. Functional organizations remain, utilizing formal communication mechanisms, such as drawing systems, design specifications, manufacturing plans and memos, still the standard business process. The DBTs were established to facilitate the existing process.

Most members of the 777 management team understood the value of bringing together experts from all of the functions during the design stage of a product. The concept of the multi-disciplinary design build team was developed over a period of years, beginning with the design of the 7J7 airplane in the mid-1980s. DBTs became the core of the concurrent engineering strategy on the 777. At its peak, the program had 255 functioning DBTs.

By definition, the design build teams were responsible for a specific portion of the overall airplane design. For instance, one DBT may have responsibility for the forward fuselage of the airplane, another for the insulation which goes into the fuselage; teams were assigned to work on the wing, the control surfaces, the struts, the stowbins, etc. In addition, other teams were commissioned to look into specific issues for design or material selection. Finally, other teams served as integrating mechanisms for lower-level DBTs. As an example of this cross-section of team charters, Figure 2.3 lists the active DBTs found in the Payloads Engineering organization during the peak of the 777 design activity.

Membership on the DBTs was somewhat variable, depending on the system or substructure being designed. Figure 2.4 describes the membership

Figure 2.3

List of Design Build Teams

Payloads Engineering

Topic or Task

- Payloads Integration
- Systems Integration
- Cargo Systems
- Potable Water
- Escape Systems
- Galleys/ Underfloor Refrigeration
- Passenger Service Units
- Cargo Furnishings
- Video
- Lowered Ceilings
- Galleys
- Lighting
- Placards
- Emergency Equipment
- Sidewalls and Vents
- **Insulation**
- Crew Rest
- Closets
- Floor Coverings
- Lavatories
- Stowbins - Outboard Center
- Interior Flexibility
- Interior Integration
- Door and Doorway Linings
- Oxygen Systems
- Seats
- Exterior Markings
- Cabin Management System Integration
- Waste Systems
- Partitions

Figure 2.4

Design Build Teams

Typical Composition by Discipline

Example: Insulation Blanket DBT

Discipline	Number of Participants
Payloads Engineering **	6
Insulation Mfg. Engineering **	3
Mfg. Eng. - Fab shop	1
Quality Assurance	1
Everett - Mock-up	2
Fab shop Producibility	1
Factory	1
Weights engineering	1
Environmental Control Systems	1
Flight Deck Engineering	3
Flight Deck Mfg. Eng.	1
Materiel Division	1
Customer Services	1
Mfg. Research and Development	2
Design-to-cost (Finance)	1
CAD/CAM Applications	1
Reliability Engineering	1
Structures Engineering	1
Boeing Materials Technology	1
Fab Shop Scheduling	1
Material Handling	1
Noise Engineering	1
Total identified membership	33

** Representatives from these organizations served as co-leaders of the DBT.

of a typical design build team. As suppliers for certain portions of the components were identified, members might be added and others subtracted. The number of team members also varied between teams. A typical team was comprised of 15 to 20 permanent members; however, many teams had meetings of 25 to 30 people or more if the issues involved were thought to impact many organizations.

One strategy that amplified the impact of the design build teams was the physical co-location of personnel from various design engineering and support organizations connected to a design build team. Although there is not yet clear evidence suggesting that the quality of the designs were better, in instances where complete co-location was implemented, overall success of the team as judged by management and engineers themselves was considered greater. Unfortunately, several facility and political barriers prevented the complete co-location of all organizations and teams.

Effectiveness of the DBTs was often directly linked to the effectiveness of the team leader. The process called for shared leadership, with the design engineer for a given section or subsystem and a manufacturing engineering representative were considered as team co-leaders. Ideally, the design engineer would act as the primary leader during the earlier periods of design, while the manufacturing engineer would take over the primary position during the detail design stage until delivery of the airplane. The role of the DBTs after the development phase of the 777 program ends is still undecided as of this writing.

The reality and demands of the program meant that there was a great diversity in the effectiveness of DBT leadership. First, the organizational level of the DBT leader was variable across disciplines and managers. In some cases the DBT leader from engineering was an engineering supervisor, while on other teams the lead engineer served in this role. Manufacturing engineering representatives varied even more. In most cases, lead engineers or experienced technical leads represented the organization. However, on some occasions, a lack of skilled personnel required some rather junior-level engineers or technical people to take on the leadership roles. This dichotomy between design engineering and the lack of manufacturing leadership experience often shifted the balance of power on many teams toward design engineering.

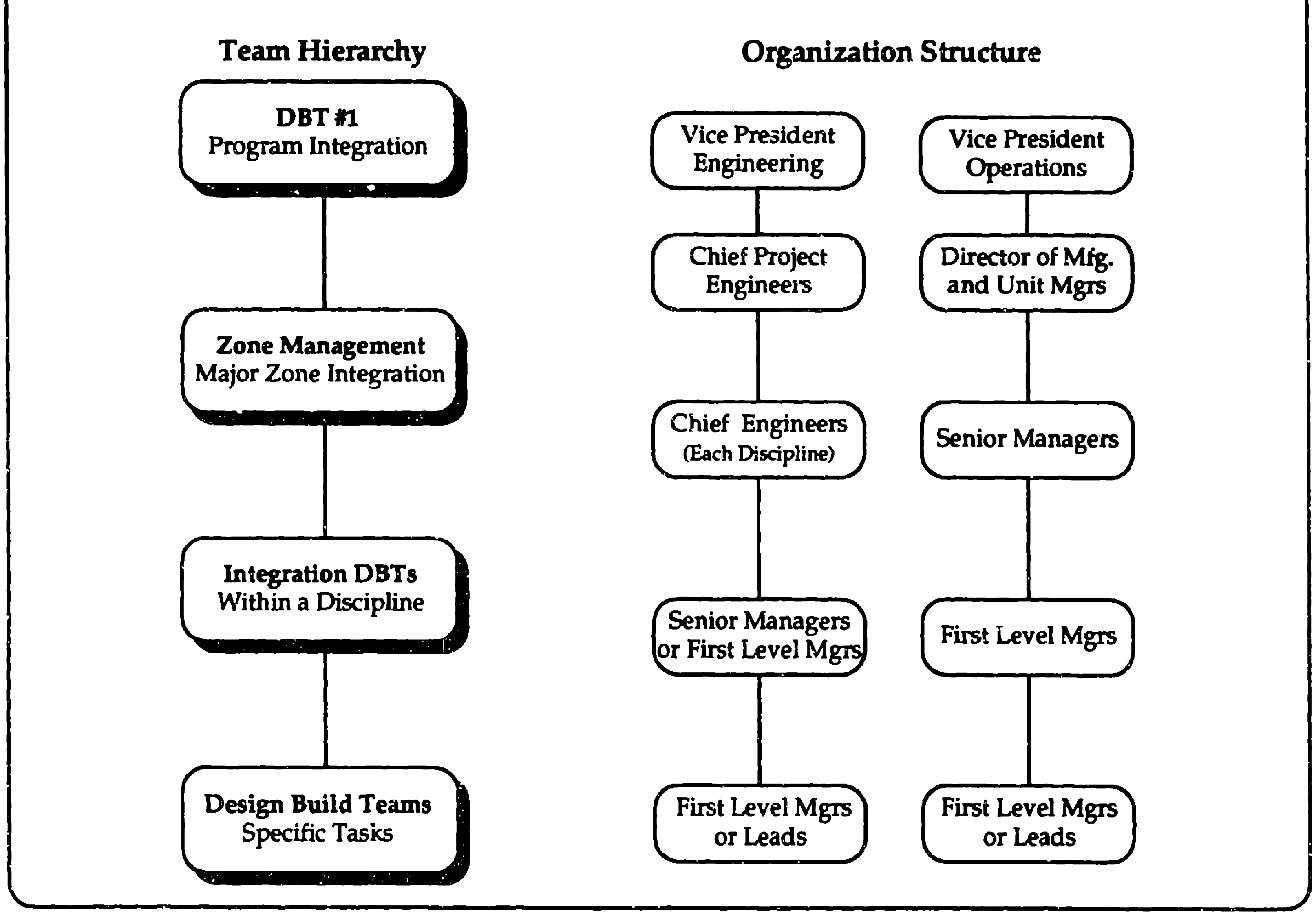
Leadership styles and the organization skills of the DBT leaders were also critical to the success of the team. Some teams seemed to flounder as clear meeting agendas, team goals, and basic team enthusiasm waned under poor leadership. Many blamed the ineffectiveness of a limited amount of leadership and DBT training. Others felt that, in certain instances, the team leader was not the best person selected for the position.

Integration of designs from all 255 different DBTs was a major challenge. How were all these separate designs to be put together into a coherent manner? The concept of "Integration DBTs" was utilized by most of the upper-level management on the program. These teams involved managers and team leaders from the lower level DBTs. During long design reviews, these integration teams painstakingly reviewed the designs of each DBT and looked for potential problems at the points of interface. Integration teams at even higher levels of management worked to integrate major substructures or subsystems (i.e. payloads into fuselage). Figure 2.5 shows the hierarchy of design build teams found on the 777 program.

The concept of integration teams evolved as the program went forward. Initially, no single group was responsible for a specific "zone" of the airplane. Later, it was found that this omission was not acceptable and a

Figure 2.5

Hierarchy of 777 Program Design Build Teams



"zone management" system was instituted whereby one design discipline took responsibility for integration of designs within a specific zone. For instance, the "crown" or top of the airplane was defined as a zone managed by the environmental systems group because so many systems were included in the area above the ceiling panels.

In general, the DBT structures used on the program were a large success. Of all the positive affirmations provided during my research by managers and engineers on the program, the most frequent was the co-location and teaming of cross-disciplined engineers. However, based on my analysis of the approach, some changes should be made on the teams to provide a more universal vision of the global requirements of the airplane and products expected of the team upon completion of each design stage.

2.7 Hardware Variability Control (HVC)

Hardware Variability Control was a 777 initiative to gain greater control of critical features on component parts and assemblies. Previously, part specifications and assembly tooling controlled critical interfaces (as discussed in Appendix 1). Quality of the final design was ensured by the tooling itself (go/no go gauges were utilized at critical locations on the product), and quality assurance inspectors who measured deviations from the drawing to determine whether they were within tolerance. However, the total philosophy toward quality and tooling is transformed with the use of a HVC concept.

The focus in HVC is on the component parts and the processes used to produce detail parts and assemblies. Processes in control and capable of meeting criteria based on next-level assembly interface requirements will produce detail parts that will fit. Sub-assembly processes in control and capable that meet their next-level assembly requirements will fit, and so on. The result is a quality product based on quality processes, not inspection. This approach requires much more data to evaluate the true capability of processes, as well as an enlightened supplier base who will attack and reduce variation in manufacturing processes even when their products are within design specification. However, if this process is implemented the gauging and rework requirements for the airplane will be substantially reduced.

A critical aspect of this approach is the determination of which characteristics on a component part or assembly should be "key". A hierarchical approach for identifying the key characteristics was applied. First, top-level assemblies (i.e. an entire fuselage section or a wing) were analyzed to determine the key points of interface. The process continued sequentially down the component parts tree until the lowest level detail parts were analyzed and key characteristics identified. Good technical judgment, current tool indexing schemes, and experience on past programs were the main determinants of the key characteristics at each level.

I believe that an opportunity exists in the HVC process: analytical tools were not used during the process of establishing key characteristics. The design build teams, particularly the manufacturing engineers, established the key characteristics for a given substructure or subsystem very early in the program. However, there was no method of feedback related to the selection of the characteristics until the airplane moves into production. A computer based analytical tool could help provide this feedback before these "key characteristics" are determined.

3. Concepts of Concurrent Development

3.1 Search for Improvement

While all the results are not available at this writing, success of the 777 concurrent design process seems assured. Through the use of CATIA™, product integration at the design stage has improved tremendously over past airplane programs at the company. The organization's co-located teams of engineers developed a quality product, which will be built more cost-effectively.

Yet, as with all parts of the Boeing, there is a search to improve the current process. The remainder of this document is dedicated to the improvement of the design-build process, using the framework established for the 777 program as a springboard. In order to make these improvements, I will concentrate on providing a new conceptual model for concurrent product and process development; one which focuses on an expanded definition of the term "concurrent."

As stated in the first chapter, I believe that the area in which the 777 process could improve is in true "integration." Completing product and process design in parallel (concurrently) is not enough. Doing so while maximizing integration and ensuring all disciplines have voice in the process (design democracy) is the key. Below I will investigate this expanded definition in terms of existing models for product and process development.

3.2 Models for Product and Process Development

There is much discussion in the literature regarding models for product and process development. Below is a brief discussion regarding popular models for development and how they relate to the Boeing Design Build Process.

Sequential Model

Traditional viewpoints regarding design have taken a very functional, sequential design approach. As one functional discipline is finished with a portion of the design, it is passed onto the next function (depicted in Figure 3.1), much like a relay race. The design is passed on to the next stage only after the first stage has completed their task.

Sequential design has the ability to satisfy the constituencies of the prime design group, the group primarily responsible for the product design. Prior to passing the design onto the next organization, the current controllers of the design will be satisfied from their point of view. Depending how far the culture has shifted from the "over the wall" syndrome of design, the next organization to receive the design for review or "sign-off" will have less to say about the final design than the originating group. The further away from the originating design group, the less say in the final design. "Sign-off" of the design by the downstream organizations is not a good substitute for having concerns heard early in the process and incorporated in the design.

Concurrent Development

More recent discussions in the literature have focused on the concept of concurrent product development or simultaneous engineering. We are looking for a system that acts more like a rugby team than a relay team, passing the ball within the team, often backwards as a sacrifice to achieve the ultimate team goal[1]. In theory, concurrent engineering will allow firms to satisfy these "design imperatives" for future success:

- Be quick and responsive in the design of products;

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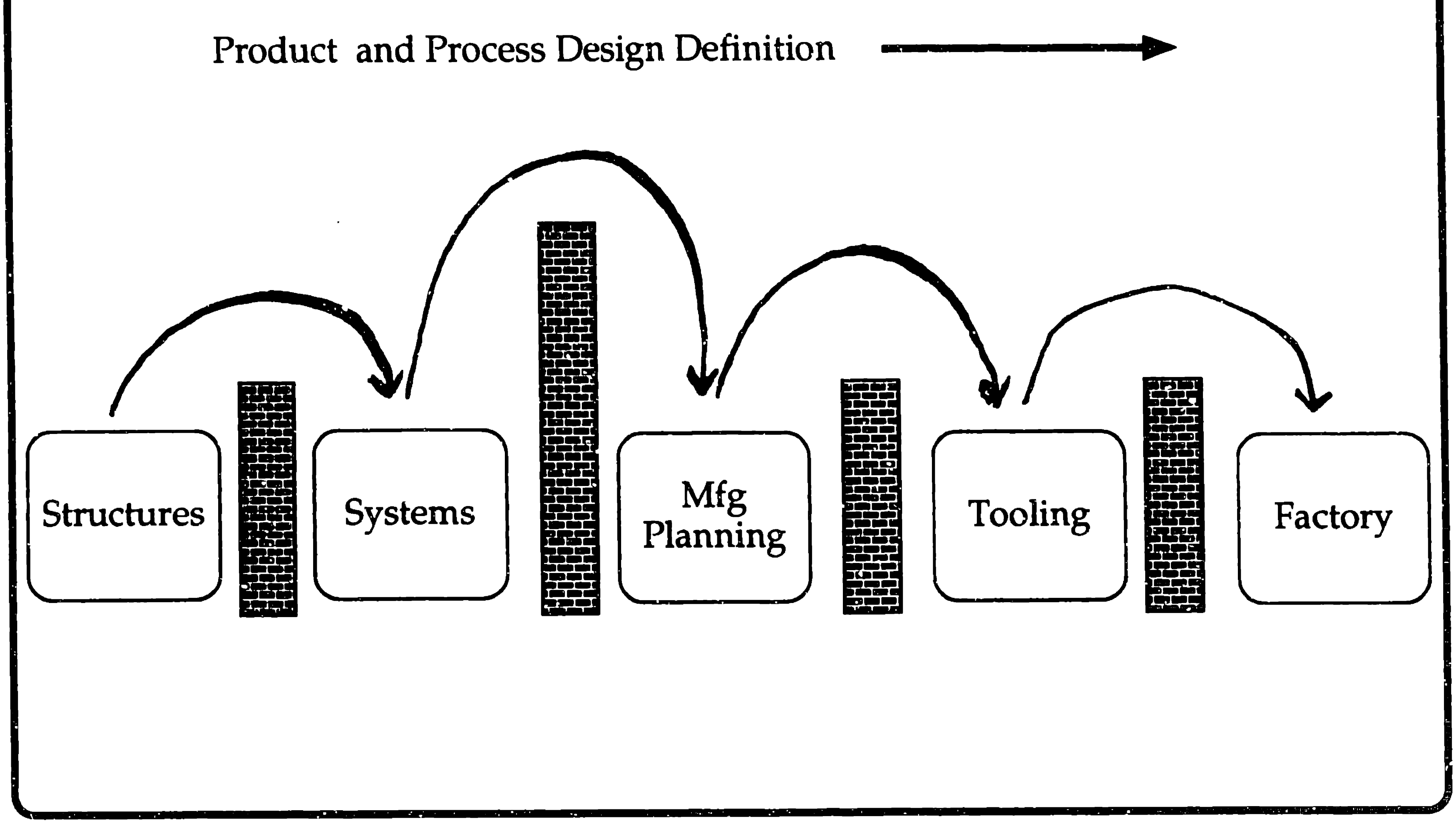
[1] Evans, Bill*Design Management: A Handbook of Issues and Methods* edited by Mark Oakley, Chapter 41,Basil Blackwell , Oxford, 1990.

Figure 3.1

Traditional Sequential Development Process



- Do so with high development productivity; and
- Provide products with distinction and integrity.[2]

While these analogies and descriptive phrases do summon us to a new way of operating in the product and process development environment, there is much confusion and misunderstanding among the "experts" as to what the phrase "concurrent development" really means. For instance, some define concurrent development from more of a traditional functional viewpoint, such as Poli and Graves, who defined concurrent engineering as "a design process which is able to combine the concerns of marketing, engineering, manufacturing and field service into one integrated procedure"[3].

Others, such as Donald Smith (Ford Motor Company), believe there is a difference between the terms. "Concurrent engineering means [design] occurs at the same time with two groups in communication. Simultaneous engineering means groups actually do it together."[4] Finally, others seem to combine the need for functional groups working together with the need to simplify the design process in general and do away with much of the systematic control currently on the designers, such as in the Lockheed Skunk Works[5] .

The best descriptions of concurrent product and process development get to the essence of cross-functional thinking and multi-directional information flow. For instance, in a recent book by James Nevins and Daniel Whitney of Draper Laboratories concurrent is described as "That the design of the product

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[2] Wheelwright, Steven and Kim Clark, *Revolutionizing Product Development* , The Free Press, New York, 1992, pg. 5.

[3] Poli, Corrado and Robert Graves, "Return Your Competitive Edge With Concurrent Engineering", *Controls & Systems*, April 1992, pp. 28-31.

[4] Cook, Brian M., "Design Gets a Face Lift", *Industry Week*, November 18, 1991, pp. 46-50.

[5] Vasilash,Gary S., "How Your Team Can Fly as High as An SR-71", *Production*, February 1992, pp. 62-66.

and its manufacturing system are carried out more or less simultaneously"[6]. Another author discussed the topic this way, "Concurrent engineering requires multi-directional information flow, versus the unidirectional flow associated with the traditional sequential engineering approach."[7]

Therefore, the term "concurrent" does not fully define the new mindset necessary for world class product and process development. The new development paradigm must place production of a product, the customer's use of the product, and the business strategy of the enterprise foremost in the minds of designers. Japanese have revolutionized shipbuilding using the philosophy that design is a subset of production.[8] Once the functional characteristics have been determined, the rest of the design is determined by how it will be built[9]. I will keep the term concurrent development, but expand its definition to truly capture the critical success factors for any large scale product development project.

3.3 Expanded Concept of Concurrent Development

The definition of "Concurrent Development" above is not inclusive of all aspects of this powerful philosophy. The definition should be expanded to encompass three distinct and important concepts:

- Concurrency of Development
- Design Consensus-Building; and
- Integration.

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[6] Nevins, James and Daniel Whitney et. al.,*Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*, McGraw-Hill, New York, 1989, pg 14.

[7] Creese, Robert C. and L. Ted Moore, "Cost Modeling for Concurrent Engineering", *Cost Engineering*, June 1990. pg 23.

[8] Nevins, James and Daniel Whitney et. al.,*Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing*, McGraw-Hill, New York, 1989, pg. 61.

[9] Ibid.

When developing a product as complex as an airplane, designing integral systems, components, and manufacturing processes at the same time is not enough to provide a product which will meet all customer and strategic requirements.

Concurrency of Development

The time it takes to get a new product from concept to market has been shown to be a critical part of the product's ultimate success.[10] Based on an economic model developed by Preston Smith and Donald Reinertsen, technology products coming to market six months late, but within budget, will have the same negative profit impact over five years as a product out on time, but 50% over budget.[11] The result is simple, time matters in product development.

It only makes sense that work done by engineers at the same time, rather than sequentially, will reduce the total time necessary for product development. However, a key to success using this new approach is the minimization of rework or iterative cycles between design groups. Because of the need for design consensus-building and integration, concurrency itself is not sufficient to make major changes in product development.

Design Concerns and Consensus

Equal "representation" of all constituencies during the initial stages of the design process is critical to its ultimate success. During this period of design discovery, many ideas, concerns, and concepts are discussed, analyzed

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[10] Blackburn, Joseph, *Time Based Competition - The Next Battle Ground in American Manufacturing,*, Business One Irwin, 1991, pp. 3-11.
[11] Smith, Preston and Donald Reinertsen, *Developing Products in Half the Time,* Van Nostrand Reinhold, New York, 1991, Pg. 40.

and subsequently incorporated or discarded. Each disciplines bring specific requirements and historic knowledge to the table. Everyone has an opinion.

Early in the design process, these constituencies should be heard in an unfettered discussion of concepts and proposals. Team processes such as brainstorming will help the team reach a final solution. All positions are included in the discussion, but not all are satisfied completely.

While discussion about the issues surrounding a design are critical, coming to a consensus which meets the global objectives of the company is even more important. As is often quoted at Boeing, "Design of an airplane is a compromise." Figure 3.2 shows a popular cartoon at Boeing depicting the views of design from different perspectives. If the aerodynamics group were to design it, the airplane would appear as a large airfoil. Fuselage designers would prefer a boxy with little or no wing. Stress engineers would like a the equivalent of a structural beam. Finally, production engineers would most likely want the simplest design possible.

Of course, what engineers want in a design is not the most important factor. Instead, the plethora of constituents, such as the FAA and the various faces of the customer (operations, finance, ground maintenance), are often the determining factor in the final design. All concerns and desires of all the representatives can not be met, a compromise is reached. The act of development becomes a juggling act (Figure 3.3), not resulting in a true compromise, but in a synergistic, integrated system meeting all essential safety of flight requirements, as many customer requirements as possible, as well as mitigating as many issues and concerns among the constituencies as possible. The end product will not be optimum from the standpoint of any one group, but the product will be the best possible design for the company

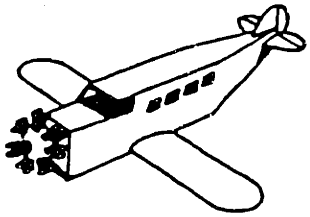
Figure 3.2

DREAM AIRPLANES

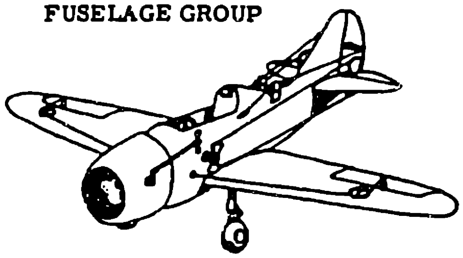
A completed airplane in many ways is a compromise of the knowledge, experience and desires of the many engineers that make up the various design and production groups of an airplane company.

It is only being human to understand why the engineers of the various groups feel that their part in the design of an airplane is of greater importance and that the headaches in design are due to the requirements of the other less important groups.

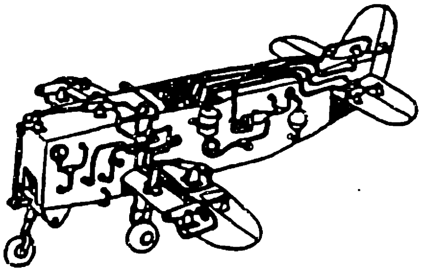
This cartoon "Dream Airplanes" by Mr. C. W. Miller, design engineer, indicates what might happen if each design or production group were allowed to take itself too seriously.



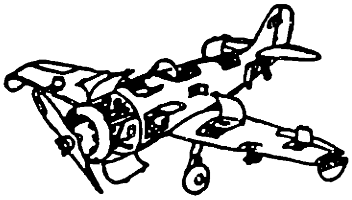
FUSELAGE GROUP



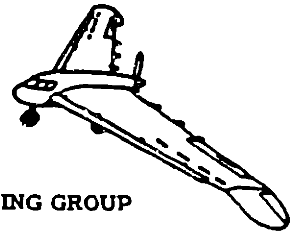
CONTROLS GROUP



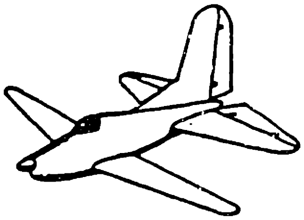
HYDRAULICS GROUP



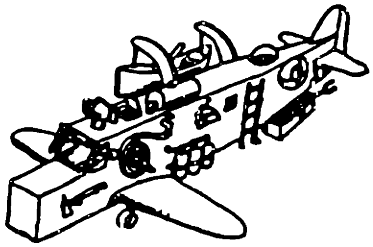
SERVICE GROUP



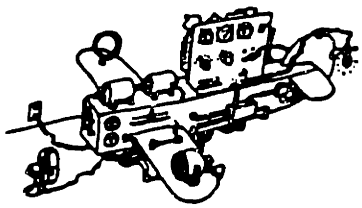
WING GROUP



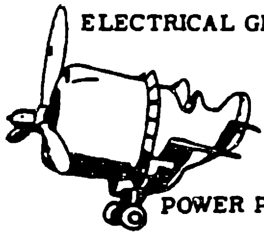
EMPENNAGE GROUP



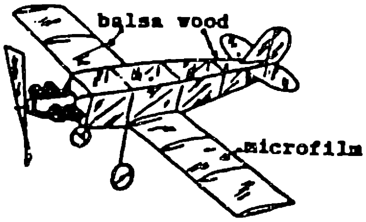
EQUIPMENT GROUP



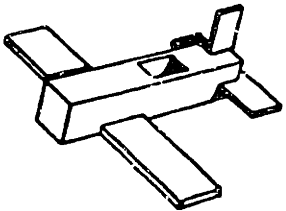
ELECTRICAL GROUP



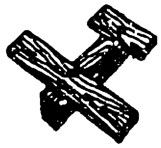
POWER PLANT GROUP



WEIGHT GROUP

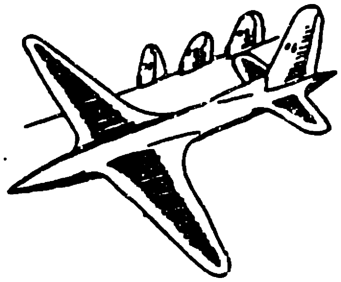


LOFT GROUP

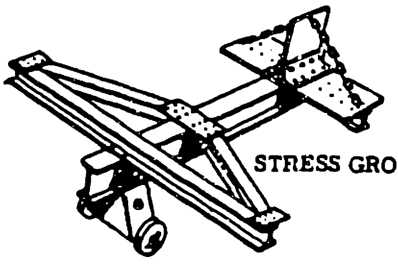


PRODUCTION ENGINEERING GROUP

ARMAMENT GROUP

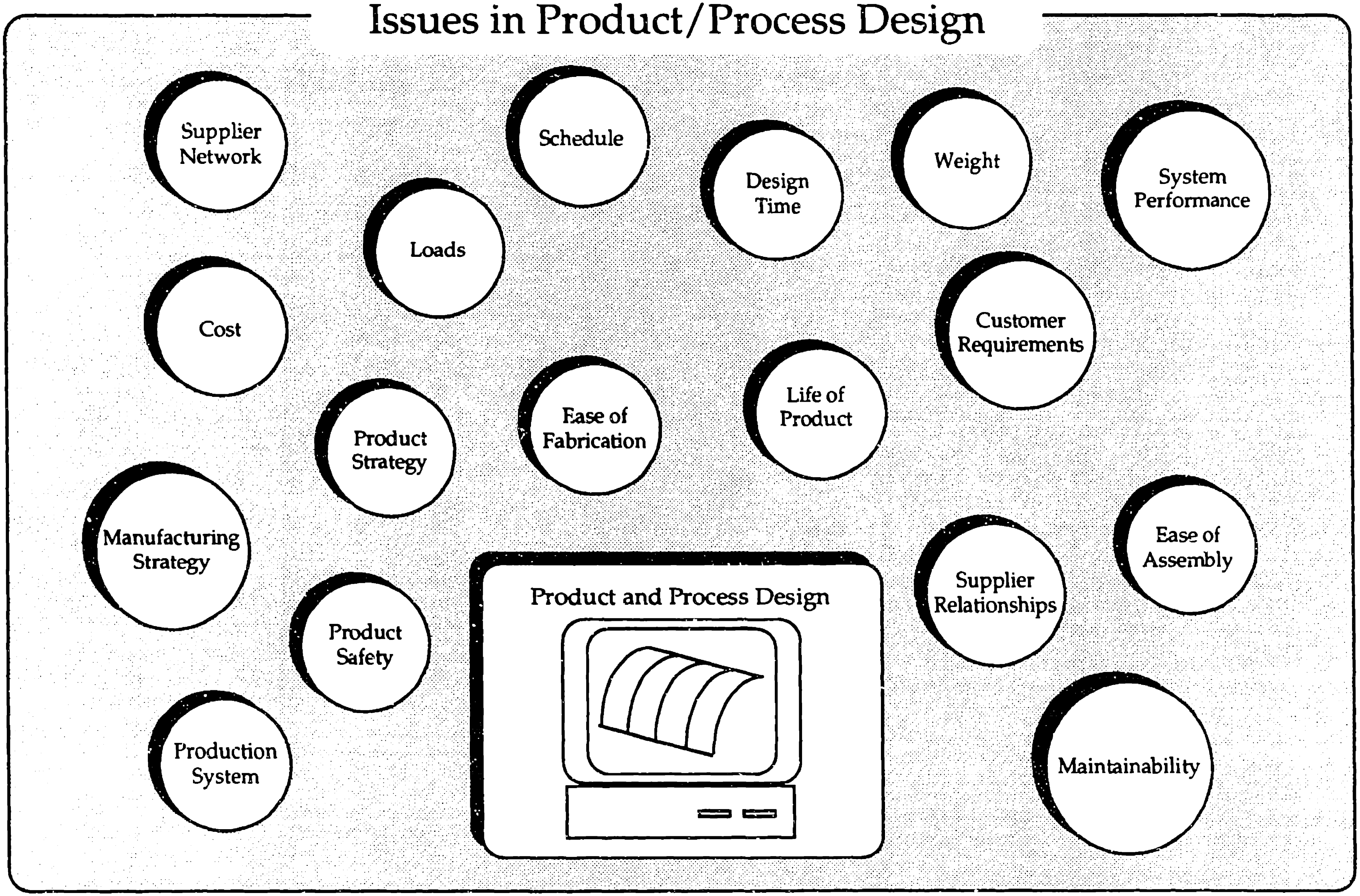


AERODYNAMICS GROUP



STRESS GROUP

Figure 3.3



Issues in Product/Process Design

and customer as a whole. In short, the goal of the development team should be to move toward the global optimum.

Sequential design processes only went a portion of the way toward discussion of design concerns early in the development process. Downstream organizations from the "prime" design group seldom had a voice. Design by consensus was unthinkable. By utilizing "drawing sign-offs" by the various downstream disciplines, designs provided by the prime design group could be effectively vetoed until changes were made. However, design input by most constituencies was too late to shape the design during the important conceptual period.

A team approach to concurrent development seems to bring "equal representation" to the design. While each discipline is responsible only for its portion of the design, discussions must take place early in the process. Concerns are voiced regarding past problems. Issues are raised about the feasibility of the concurrently derived configuration. Finally, a design results which does not reflect only the prime design group's ideas but includes the spirit of all comments made during the development period.

While a development process for products as large and complex as an airplane must maintain a high level of design consensus-building, there must be caution in how far the development process goes toward integrating different disciplines. Integration of product and process designs are critical for the success of the concurrent approach to product development. However, approaches based on autonomous work teams (e.g. Lockheed Skunk Works) could lead to a situation where stronger disciplines move the entire team in the wrong direction (the "groupthink" phenomena described by Irving Janis[12]). For instance, without a balance of power and design consensus-

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[12] Janis, Irving, "Groupthink", *Psychology Today,* 1971.

building, an airplane design team might produce a design that optimizes the fabrication of the component, but increases the assembly and reduces the quality of the assembled product.

Integration

Integration of the design becomes the critical aspect of the development process. All components, systems, and manufacturing processes must be brought together prior to production (integrated) to ensure the success of the product. Completing the design of product and process at the same time is important, but without a continual intermixing of information and integration of designs and plans, the global optimum may not be reached.

What is meant by "integration" in this paper is the interlinking, experimentation, feedback, and correction necessary for two groups to know that the design of each component, as well as the whole, meet agreed-upon requirements. It is not enough to design a component which meets requirements, the system (and interactions within the system) in which it fits must meet the global objectives.

Integration does not occur simply through design consensus-building. This author takes a more forceful view of design integration; only a disciplined process of intertwining product and process concepts and geometric data can result in true integration. A designer must:

- Understand how mating components fit with his/her design;
- Determine the interactions from dynamic components; and
- Gauge the impact of the process design on the product.

A period of discussion and consensus-building is probable to accomplish integration, but specific steps must be taken to gain the information necessary to determine if the product will work using the as-designed process, per the current product design. The assembly is "built" (in the computer) even before it reaches production. Problems with incompatibility are solved long before tools or parts are fabricated or the design finalized.

While technical analysis of individual components or subsystems is an important part of today's engineering discipline, there are few tools which allow engineers from different disciplines to examine the system as a whole. Technical analysis tools are needed to enable the integration of product and process design as described above. In addition, a product development methodology which utilizes a more disciplined approach to project management could bring about the required integration by integrating the development activities themselves. Later I will propose new models and technical tools for accomplishing this design integration.

3.4 Product Development at Boeing

The design of the 777 has brought about many changes at Boeing regarding the development of new aircraft. However, there continues to be a great deal of room for improvement in the processes used. Development initiatives, such as the "design build teams (DBTs) and the "concurrent product definition" provided an enhanced opportunity for design consensus-building and concurrency, but had limited success in moving the company toward true integration. In the following chapters I hope to develop a new way of looking at the design of an airplane and outline how the company can move toward an effective balance between each of these important elements of concurrent development.

4. Proposed Model for Product and Process Development

4.1 Focus on Integration

Concurrent design and consensus-building are not enough. The next models of product and process development must focus on integration; integration of product design disciplines, integration of product and process design, and integration of the requirements driving the entire development project.

A model will be described in this chapter which will attempt to build upon the concurrent development model (i.e. Boeing 777 Design/Build Process) to provide a development process that is both integrated and concurrent. This new model must move past the paradigm of compartmentalized design disciplines, which limits the current framework. However, consensus-building regarding the aspects of design must also be accomplished.

4.2 Interface Information

While the 777 program was a paradigm shift for the company in the use of concurrent development, the basic assumptions of how design information is disseminated among all constituencies have not changed since Boeing's first airplanes. Concepts and preliminary drawings were discussed by design engineers in the design build teams to elicit comments. Yet, the critical dimensions and interface points on the design, which impact groups designing systems, tooling, customer services, and fabrication, were not "frozen" until the end of a designated design stage. Therefore, large packages of frozen geometry were passed downstream at one time, a situation common in the sequential model of concurrent development.

Using a manufacturing analogy, the data are *batched* in large quantities and sent to the next step. An alternative analogy would be a *pull* or *just-in-time* (JIT) system.[1] A pull system approach would require the transfer of much smaller batches or discrete bits of design information to groups who need the information in formulating their design. It would also require the freezing of small portions of the design as the design evolves.

An example of the types of interface information necessary to complete even a simple product and process design is shown in Figure 4.1. In the example, information shared in order to design brackets used to install tubes or ducts for one of the airplanes support systems (e.g. hydraulic system). On the 777 program, the systems design group has responsibility for designing the system, but a structures design group has responsibility for including systems bracketry into the structures design. Therefore, the exchange of timely, accurate information becomes critical if both groups are to be "on schedule".

What information is needed? For the structures designers to design brackets, do they need a complete systems design? No; functional intent and approximate location of brackets are the only data needed at the early stages of the design. Do the loads engineers need a completed design to estimate the structural loads necessary for the bracket and the supporting structure? No; only an estimate of the total load carried by the bracket is necessary to estimate the total structural loads exerted on the entire structure.

A designer's first inclination is to pass on only completed designs. Yet in many cases (as in the case in Figure 4.1) there is no reason to pass on the entire design. The transfer of specific bits of information (interface

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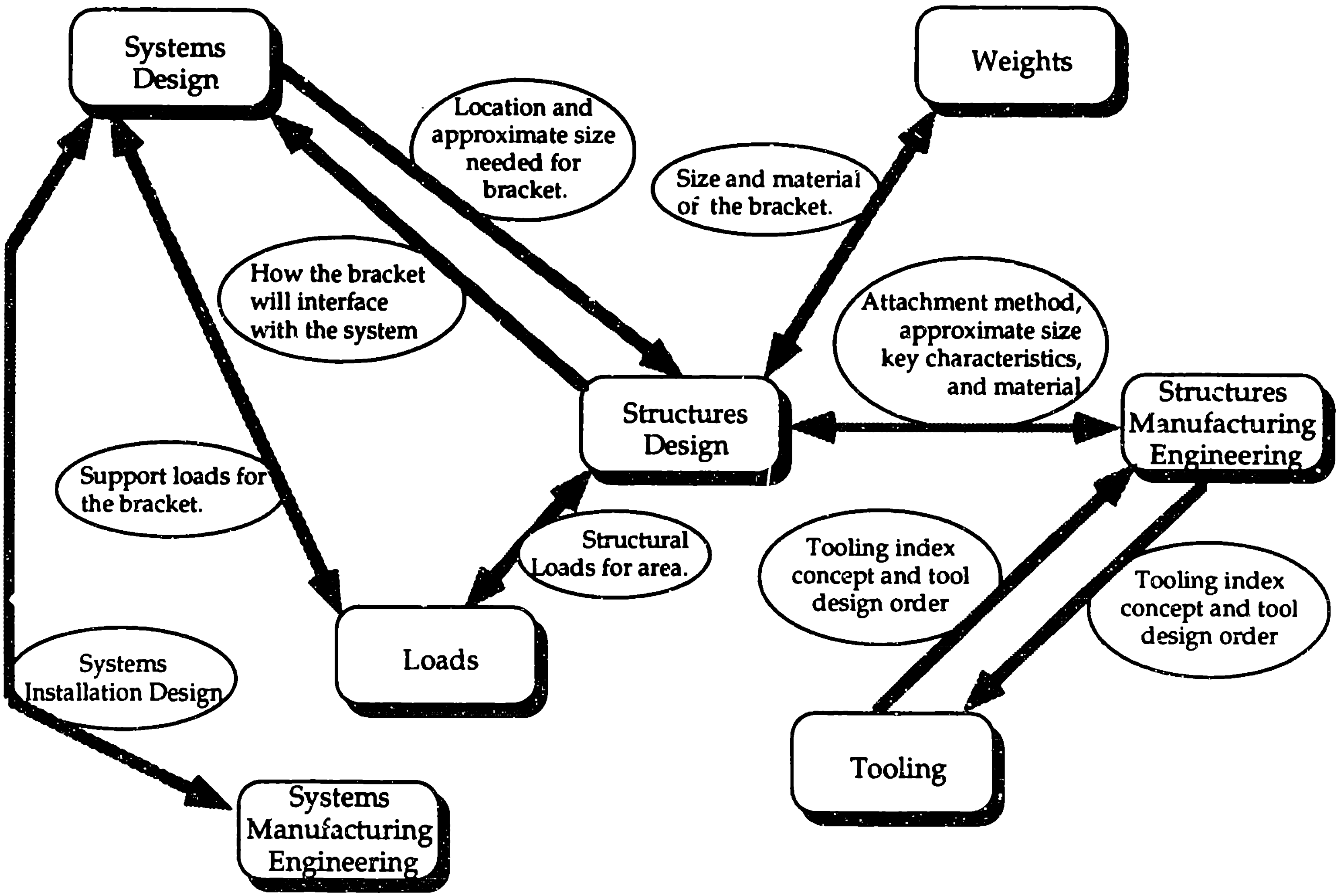
[1] Blackburn, Joseph,*Time-Based Competition: The Next Battle Ground in American Manufacturing,* Irwin, Homewood, IL 1991, pg. 148 -152.

Figure 4.1

Example of interface information.
Design of a systems bracket (product and process)



information) should be accomplished just in time for the next group to do their job. Thus, a pull information system is born.

It is important to note that product concepts and partially completed designs should still be shared among all team members "early and often". However, the bits of information which are critical to the next stages should be complete and frozen before passing them down the line.

Concentration on interface information requirements will make the job of scheduling the activities of development more complex. However, by passing specific bits of information, rather than scheduling only larger completed packages of information, the firm can ensure that designers are completing tasks only as information is needed; not before. For many of the same reasons small production batches reduce costs, concentrating on smaller bits of information transfer will:

- Reduce development costs by postponing completion of unneeded information until a later time;
- Reduce rework costs by benefiting from immediate feedback on small batches, rather than finding problems impacting larger batches;
- Reduce total time for development by focusing the designers on smaller bits of information, rather than getting lost in large product designs; and
- Provide for a more flexible product and process design since large batches of information will not have to be changed if requirements change mid-way through design.

The concept of interface information impacts the development process in several ways. First, it requires a new kind of integrated schedule; one which schedules both high level design events and discrete information exchanges between groups. Second, the data exchanged at each point in the process must be "frozen" with respect to the final design. Changes to information, such as locations, materials, and loads, will occur only with coordination and discussion with effected groups. Third, the concept of data processing by designers and design teams must change to handle small bits of information, yet allow integration at every step. Finally, CAD-based development tools must be available that allow this integration on a smaller scale and without much effort. Each of these areas are addressed in more detail below.

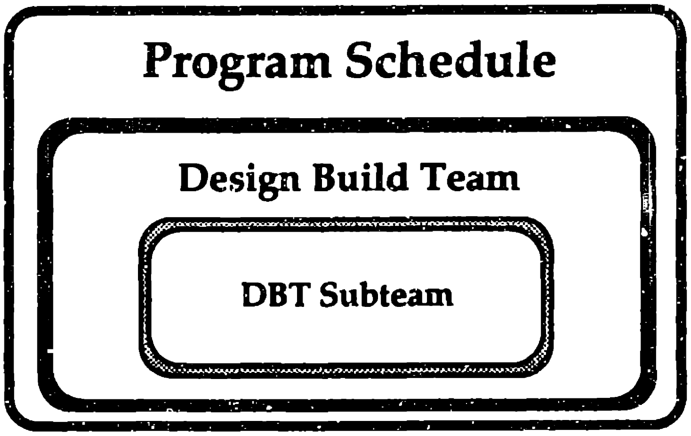
4.3 Integrated Schedule - Pull System for Interface Information

While a pull manufacturing system is also an appropriate concept for the transfer of information within a design process, the creative or intellectual nature of the design process requires some sort of integrated schedule to trigger requirements for interface information between groups. A truly integrated schedule for the entire airplane design would require the tracking of millions of bits of information transferred between groups as part of the design process.

As an alternative to this enormous scheduling task, integrated scheduling can be accomplished at different levels, with the intent of passing more of the responsibility for schedules and compliance tracking to the lowest level possible. The "levels" of the schedule would include:

- **Program schedule level** which outlines each high-level design stage and schedules major milestones for the entire airplane development project;
- **Design build team level** which requires an integrated schedule of major tasks associated with one portion of the airplane design; and

- **DBT subteam level** where engineers work intimately as a group to concurrently complete multiple tasks when interface requirements are tightly coupled between a few designers.



Program Schedule Level

The "Concurrent Product Definition" process used on the 777 provides the framework necessary for an effective program schedule. Schedule discipline at the program level is critical to achieving a final product on time. The design stages and major milestones utilized on the 777 program provide this discipline. A standard gantt (or milestone) chart is the appropriate tool to use for this level of scheduling.

Design Build Team Level

Responsibility for the design of a specific portion of the airplane is vested in the design build team (DBT). Major milestones at the program schedule level determine when end products from the team are required. However, the internal workings of the DBT, thus the internal requirements for information, are the responsibility of the members and leadership of the DBT. Interface requirements between DBTs can be negotiated based on the program-wide schedule.

A framework for dealing with the organization of complex design projects was described by Eppinger and Whitney, et. al. during a recent conference.[2] The design structure matrix is a tool to identify precedence relationships between a large number of specific design tasks and information requirements. The matrix below identifies a list of tasks (A to H) as column headers. If another task must be complete in order to finish the task in question, an X marks the column-row intersection. For instance, in the example matrix, in order to complete task C, task A must be completed. Marks in the upper right diagonal of the matrix represent precedence requirements. The left diagonal represent tasks which can be accomplished in parallel. Less significant (or secondary) precedence relationships can be indicated on the matrix by replacing the X with a number corresponding to a level of strength. Level 0 represents the strongest precendence relationship.

Design Structure Matrix

	A	B	C	D	E	F	G	H
A	X		X					
B		X						
C		X	X					
D				X	X	X		
E					X	X		X
F		X				X		
G		X					X	
H	X			X				X

The techniques presented by Eppinger, et. al. help reorder the tasks to provide a more organized design sequence. This process of partitioning allows the designer to understand the critical path (the tasks along the

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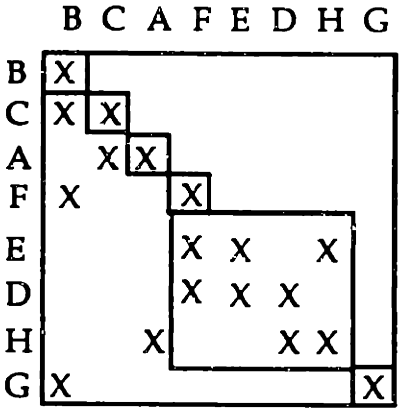
[2] Eppinger, Steven D., Daniel E. Whitney, Robert B. Smith, and David A. Gebala, "Organizing the Tasks in Complex Design Projects", *Proccedings*, ASME 2nd International Conference on Design Theory and Methodology, Chicago, IL, September 16-19, 1990, pg. 39-46

diagonal) and the tasks that should be coupled (concurrently completing tasks).

Design Structure Matrix
Partitioned to Couple Simultaneous Activities



	B	C	A	F	E	D	H	G
B	X							
C	X	X						
A		X	X					
F	X			X				
E				X	X		X	
D				X	X	X		
H			X			X	X	
G	X							X

Design build teams could use the design structure matrix to identify, sequence, and group the tasks required to complete the design according to the master program schedule. After defining the specific pieces of information required, the DBT documents the precedence relationships between the interface information requirements and tasks to be completed within the team. Next, the team partitions the original design structure matrix to reorder the tasks and group tasks that are closely coupled. Finally, the DBT establishes a critical-path driven schedule from the diagonal elements of the matrix and assigns subteams of engineers to work together to complete the closely coupled tasks, as described in the next section of this document.

Often, information requirements come from outside the established DBT. In this case, negotiation to develop a mutually beneficial schedule is appropriate. When tasks or information requirements between DBTs are shown to be closely coupled, representatives from each DBT should be assigned to a DBT subteam to complete the task, thus supporting the critical path for both DBTs.

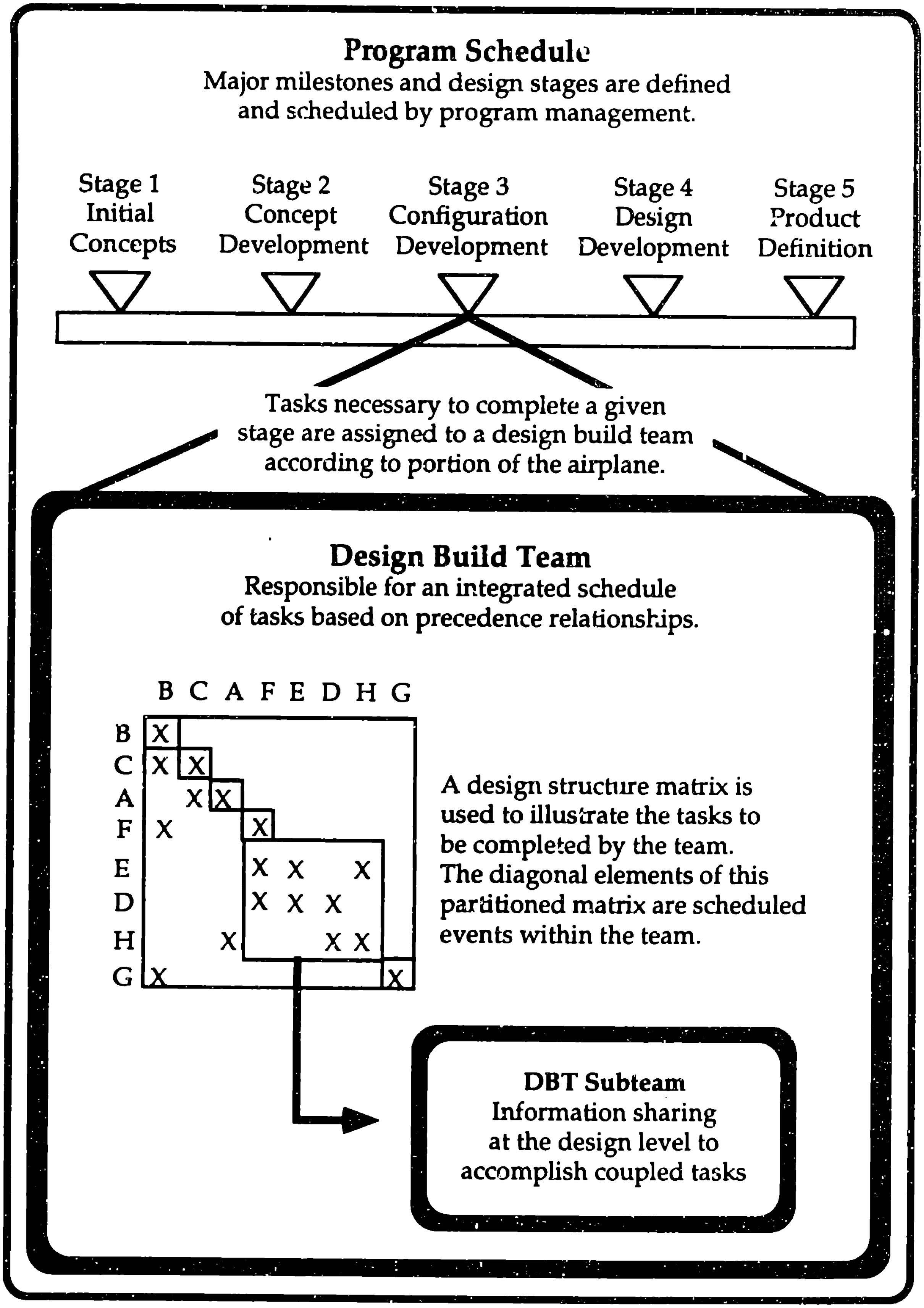
DBT Subteam Level

Whenever a collection of information requirements or tasks are closely coupled, a subteam should be assigned to complete each of the requirements. Since information passing and iteration are critical in these cases, bringing the subteam together full-time in one location will greatly facilitate the completion of the tasks. Design in these circumstances can be very informal because all the critical "players" are part of the subteam. Formality in design documentation and distribution resumes when the subteam's tasks are complete. Scheduling is based on a endpoint schedule requirement, just meeting the DBT main team critical path. Within the subteam, the information transfer is strictly a pull system; members will receive the information just when it is needed.

* * * * * * *

Figure 4.2 depicts these three levels of scheduling, along with the organization structure and scheduling tools used to accomplish the overall scheduling function. Below is a specific example, using the brackets described in Figure 4.1, which illustrates the concepts of design task structuring and integrated scheduling.

Figure 4.2: "Levels" of scheduling for product development.



Program Schedule

Major milestones and design stages are defined and scheduled by program management.

Tasks necessary to complete a given stage are assigned to a design build team according to portion of the airplane.

Design Build Team

Responsible for an integrated schedule of tasks based on precedence relationships.

	B	C	A	F	E	D	H	G
B	X							
C	X	X						
A		X	X					
F	X			X				
E				X	X		X	
D				X	X	X		
H			X			X	X	
G	X							X

A design structure matrix is used to illustrate the tasks to be completed by the team. The diagonal elements of this partitioned matrix are scheduled events within the team.

DBT Subteam

Information sharing at the design level to accomplish coupled tasks

Example of Integrated Scheduling

The brackets used to hold systems in place provide an excellent example of the kind of coupled design decision-making and interface information requirements associated with a complex product. Several steps in the process have been left out for clarity. A step-wise approach to scheduling this task is outlined below.

Creating a Integrated Design Schedule -- Bracket Example

1. A high level requirement for the design and analysis of systems brackets is identified by program management and a required date of completion is applied. The scheduled completion date is determined by an overall critical path program and tracked using traditional milestone scheduling tools. **(Program Management)**
2. Once the task assignment is received by the design build team, all major subtasks associated with the completion of systems bracket design are listed with an approximate sequential order. The list for the bracket example is found in Figure 4.3. **(Design Build Team)**

Figure 4.3: Major Design Subtasks for Bracket Design

Design Task: Design Systems Brackets

Subtasks (interface information)

A	Location and size of bracket (Systems Design)	H	Approximate size and material of brackets (Structures Design)
B	Loads required for bracket (Systems Design)	I	Approximate weight of the brackets (Weights)
C	Systems layout with bracket location (Systems Design)	J	Attachment method, size and location (Structures Design)
D	Design of the bracket related to system (Structures Design)	K	Feedback regarding bracket design (Structures Mfg. Eng.)
E	Structural loads analysis with bracket (Structures Design)	L	Tool index concept and tool order (Structures Mfg. Eng.)
F	Structural loads calculation with bracket (Loads)	M	Feedback and tooling concepts (Tooling)
G	Feedback regarding systems layout (Systems Mfg. Eng.)		

3. Precedence relationships are determined for each of the team level tasks. For instance, the approximate size and material used for the bracket cannot be determined until the bracket itself has been designed. Further more, in order to determine the weight of the bracket, the approximate size and material used must be determined. Secondary precedence relationships (information requirements which are desirable but not manditory) are also identifed. For instance, in order to design the tooling concept for locating the brackets, the approximate weight of the brackets would be nice, but not essential for the design. **(Design Build Team)**

4. The information gernerated in the last two steps is entered in a matrix format with predecence relationships identified with an X. Secondary relationships are indicated with a numeral 1. Figure 4.4 shows the initial design structure matrix (DSM) for the brackets example. **(Design Build Team)**

5. The matrix is manipulated using the DSM methodology in an attempt to obtain a lower triangular form. Figure 4.5 shows a rearranged matrix for the bracket example. Matrix manipulation was completed using a software package developed by Professor Don Steward, inventer of the DSM methodology. [3] **(Design Build Team)**

5. If a perfect lower triangular matrix is possible, as is the case in this example, tasks are "coupled", therefore, they should be completed simultaneously. Figure 4.6 shows the bracket example matrix with boxes around coupled tasks indicating simultaneous design. The DSM methodology would indicate possible groupings for the tasks such as

   Option 1: ABCD G HI JE K F L M
   An alterative to this precedence-driven sequence could be

   Option 2: ABCDGHIJE K F L M

   The first alternative ignores some substantial information relationships, while the second complicates the design tremendously by coupling a large number of tasks. **(Design Build Team)**

6. Finally, coupled tasks can be assigned to subteams of engineers and technical personnel repsonsible for each individual task. A precedent relationship has been determined for the DBT as a whole, which in turn determines the schedule for the entire design task. Internal schedules can be formulated by the subteams in whatever manner

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[3] Steward, Donald V., DSS Software, California State University - Sacramento.

Figure 4.4: Initial Design Structure Matrix for Brackets Example

		A	B	C	D	E	F	G	H	I	J	K	L	M
A	Location and size of bracket (Systems Design)	X			X			1						
B	Loads required for bracket (Systems Design)	X	X						X					
C	Systems layout with bracket location (Systems Design)	X	X	X	X					X	X			
D	Design of the bracket related to system (Structures Design)				X			X	X		X			
E	Structural loads analysis with bracket (Structures Design)				X	X		X		X				
F	Structural loads calculation with bracket (Loads)	X	X	X	X	1	X		X	1	X			
G	Feedback regarding systems layout (Systems Mfg. Eng.)	X		X				X						
H	Approximate size and material of brackets (Structures Design)				X				X					
I	Approximate weight of the brackets (Weights)								X	X				
J	Attachment method, size and location (Structures Design)		1	X		1					X	1		
K	Feedback regarding bracket design (Structures Mfg. Eng.)				X				X		X	X		
L	Tool index concept and tool order (Structures Mfg. Eng.)	X		X					X	1	X		X	
M	Feedback and tooling concepts (Tooling)	1		1	1	1			1		1		X	X

Figure 4.5: Rearranged Design Structure Matrix for Brackets Example

		A	B	C	D	G	H	I	J	E	K	F	L	M
A	Location and size of bracket (Systems Design)	X			X	1								
B	Loads required for bracket (Systems Design)	X	X				X							
C	Systems layout with bracket location (Systems Design)	X	X	X	X			X	X					
D	Design of the bracket related to system (Structures Design)				X	X	X		X					
G	Feedback regarding systems layout (Systems Mfg. Eng.)	X		X		X								
H	Approximate size and material of brackets (Structures Design)				X		X							
I	Approximate weight of the brackets (Weights)						X	X						
J	Attachment method, size and location (Structures Design)		1	X					X	1	1			
E	Structural loads analysis with bracket (Structures Design)				X	X		X		X				
K	Feedback regarding bracket design (Structures Mfg. Eng.)				X		X		X		X			
F	Structural loads calculation with bracket (Loads)	X	X	X	X		X	1	X	1		X		
L	Tool index concept and tool order (Structures Mfg. Eng.)	X		X			X	1	X				X	
M	Feedback and tooling concepts (Tooling)	1		1	1		1		1	1			X	X

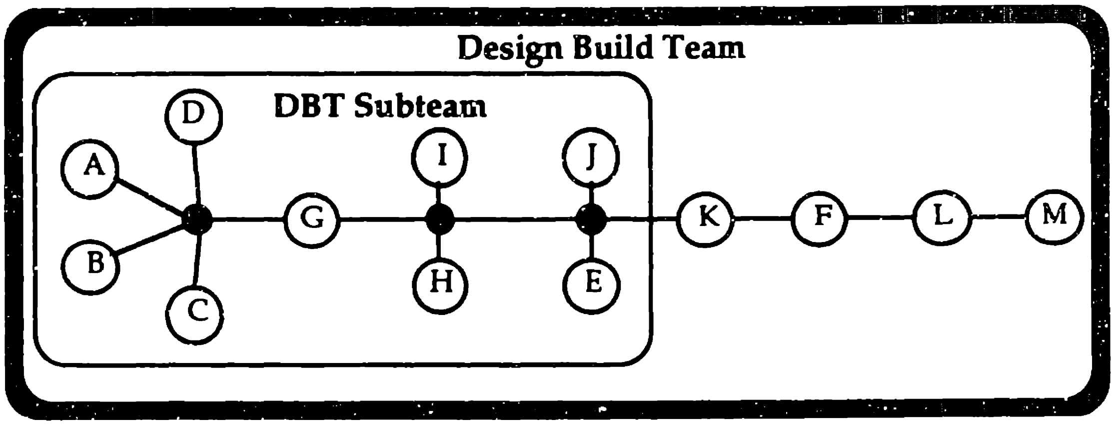
Figure 4.6: Coupled Design Structure Matrix for Brackets Example

		A	B	C	D	G	H	I	J	E	K	F	L	M
A	Location and size of bracket (Systems Design)	X			X	1								
B	Loads required for bracket (Systems Design)	X	X				X							
C	Systems layout with bracket location (Systems Design)	X	X	X	X			X	X					
D	Design of the bracket related to system (Structures Design)				X	X	X		X					
G	Feedback regarding systems layout (Systems Mfg. Eng.)	X		X		X								
H	Approximate size and material of brackets (Structures Design)				X		X							
I	Approximate weight of the brackets (Weights)						X	X						
J	Attachment method, size and location (Structures Design)		1	X					X	1	1			
E	Structural loads analysis with bracket (Structures Design)				X	X		X		X				
K	Feedback regarding bracket design (Structures Mfg. Eng.)				X		X		X		X			
F	Structural loads calculation with bracket (Loads)	X	X	X	X		X	1	X	1		X		
L	Tool index concept and tool order (Structures Mfg. Eng.)	X		X			X	1	X				X	
M	Feedback and tooling concepts (Tooling)	1		1	1		1		1	1			X	X

Legend: ☐ Option 1 ▣ Option 2

desired. Figure 4.7 below depicts the precedence network required to design the brackets. **(Design Build Team)**

Figure 4.7 Precendence Network for Bracket Design



Integrated Schedule

The bracket example shows the complexities of even simplified interface information scenarios. However, by segregating the levels (or tiers) of scheduling, an "integrated" schedule does result. The details of the information transferral between engineers in coupled tasks will be scheduled within a very small subteam structure. An overall precedent schedule for tasks associated with a major design will determined by the DBT. Finally, a schedule of development events to the design task level (i.e. "design system brackets") can be developed and tracked at the program management level.

The discipline of the design structure matrix makes this delegation of detail scheduling responsibility to the DBTs possible. Without a structured approach, the schedule at even the DBT level would be untenable. With these tools, the integration of both simultaneous and sequential tasks can be accomplished.

4.4 Evolving Design - Partial Freeze Concept

In order for an integrated schedule of interface information to be effective, another concept must be adopted; the concept of partial design freeze. Traditionally, the design of a product will be frozen at various points in time in order for interfacing groups to evaluate the design. In the case of the 777, these points of design freeze took place at the end of each design stage. As discussed in Chapter 2, information about the design was shared in the DBTs, but the majority of the design sharing and interface took place during the design freeze period. Once frozen, the designs at a certain level of detail could be changed by the design group responsible during later stages. Design freeze meant only that no additional changes could be made during the freeze period.

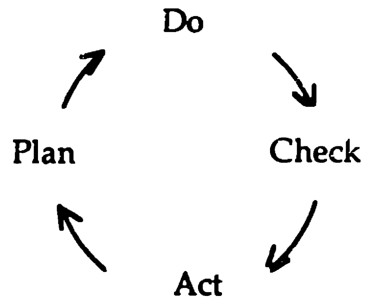
The new integrated model for product and process development must provide a different discipline to the system. Now, design freeze means that the aspect of the design frozen cannot be changed without re-coordination by all impacted engineering groups. However, rather than freezing the entire design (or as much as is complete at the end of a stage), only critical portions of the design are frozen. Again, using the design of systems brackets as an example, the basic bits of information passed from group to group would be frozen once transferred. That is, once the structures design group was able to determine the relative size and material used to fabricate the bracket and passed it on to the weight engineering group, that information will be frozen. Changes at later stages of the design can be made, but only with coordination and discussion.

At the point in time that the size and material are determined, no other details of the design are frozen, just those which are being passed onto other groups. Design information such as critical dimensions, materials, location points for surfaces, volume requirements, and fastening methods can be frozen without freezing the actual geometry. Therefore, the design evolves as more and more of the this type of information about the design is frozen. Figure 4.8 shows the variety of design elements which could be frozen early in the design.

The gated approach to design evolution is still appropriate even with partial design freeze. Now the design stages can be used as periods where concepts for the final design can be evaluated by the entire development organization. At the same time, elements of design already frozen will be included and double-checked during the freeze period. Integration of product and process can take place during these periods, and adjustments can be made in plans for the final design.

4.5 PDCA Cycle in Development

The Plan-Do-Check-Action cycle has been a primary tool for quality improvement activities for many years. First popularized in Japan, the PDCA cycle is a simple, yet powerful, model for problem-solving. [4]



In problem-solving contexts, the PDCA cycle provides a mental framework for accomplishing the task, while ensuring a quality result. One

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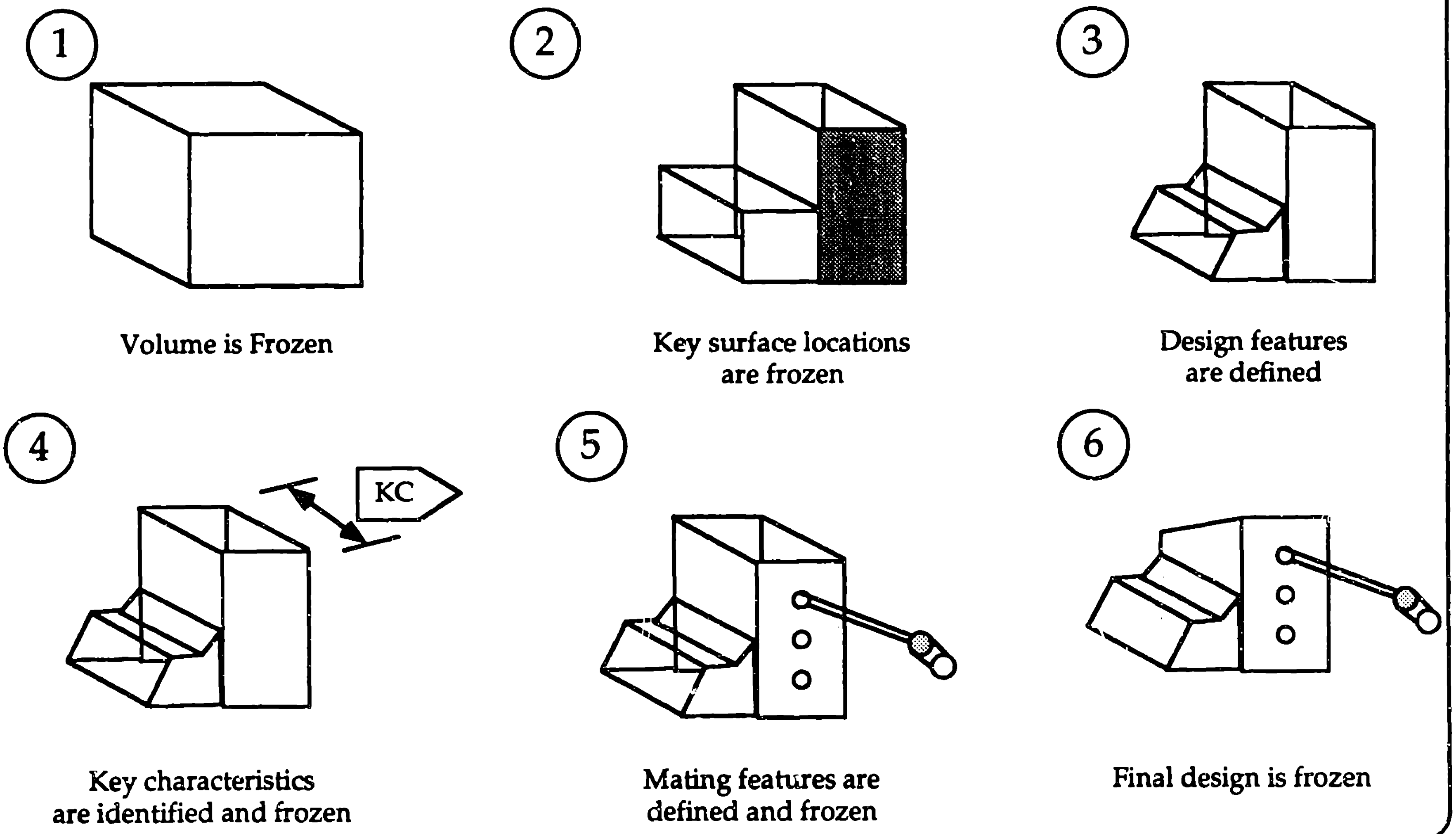
[4] Shiba, Shoji, Total Quality Management, Classnotes, MIT, Cambridge, July 30. 1991.

Figure 4.8

Design Freeze Concept

Portions of the design are "frozen" as soon as they are defined



Volume is Frozen

Key surface locations are frozen

Design features are defined

Key characteristics are identified and frozen

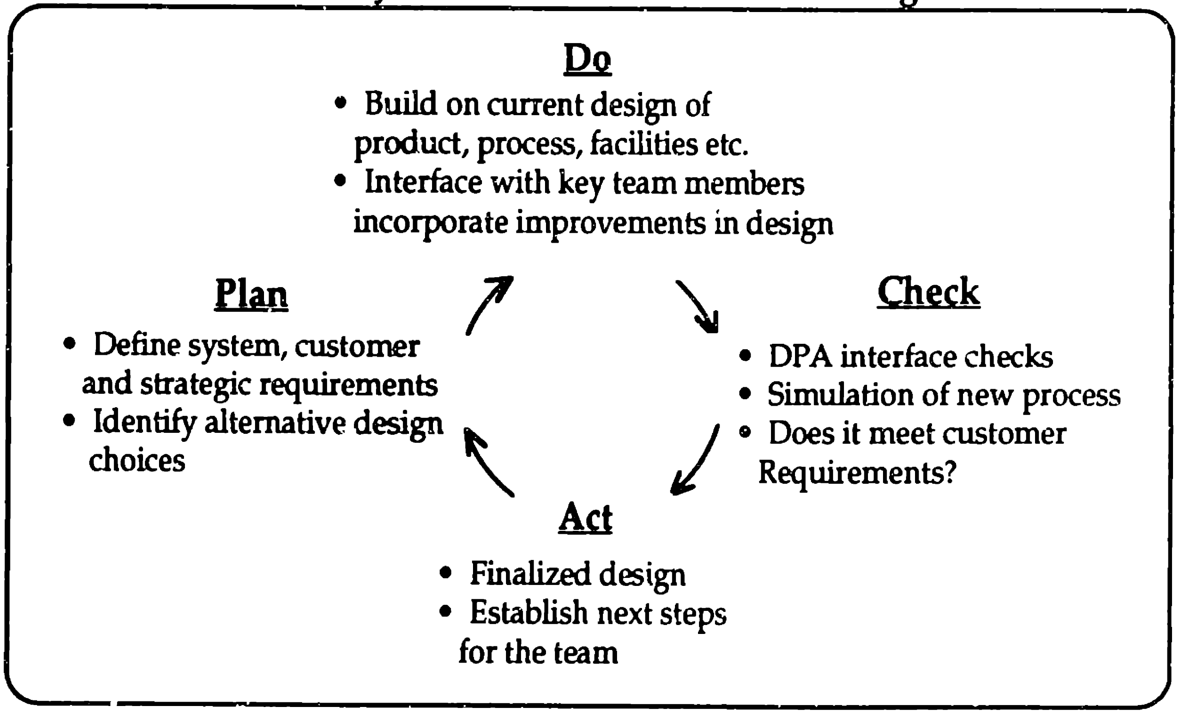
Mating features are defined and frozen

Final design is frozen

of the key steps in the process is the "check" step. In this step, the initial solution, or the initial design in our case, is checked to make sure that it functions as expected and solves the problem. In the case of product or process design, integration with other portions of the design will take place at this point. Figure 4.9 shows generalized steps taken by a designer or a DBT for each PDCA cycle during the period of development.

Figure 4.9

PDCA Cycle Used in Product / Process Design



Each time a team receives a bit of interface information from another team, an action is begun to complete the design task. I suggest that applying the PDCA concept to these periods of development will provide integration at every step in the process. Prior to releasing a frozen design element to the another design group, the PDCA cycle ensures that it meets predetermined customer requirements, is integrated with interfacing product or process designs, and provides all the information necessary for the next stages of the process. Quality and integration of design is built into the process at each discrete step of the design, not just "assured" at each stage.

4.6 PDCA Model for Design Development

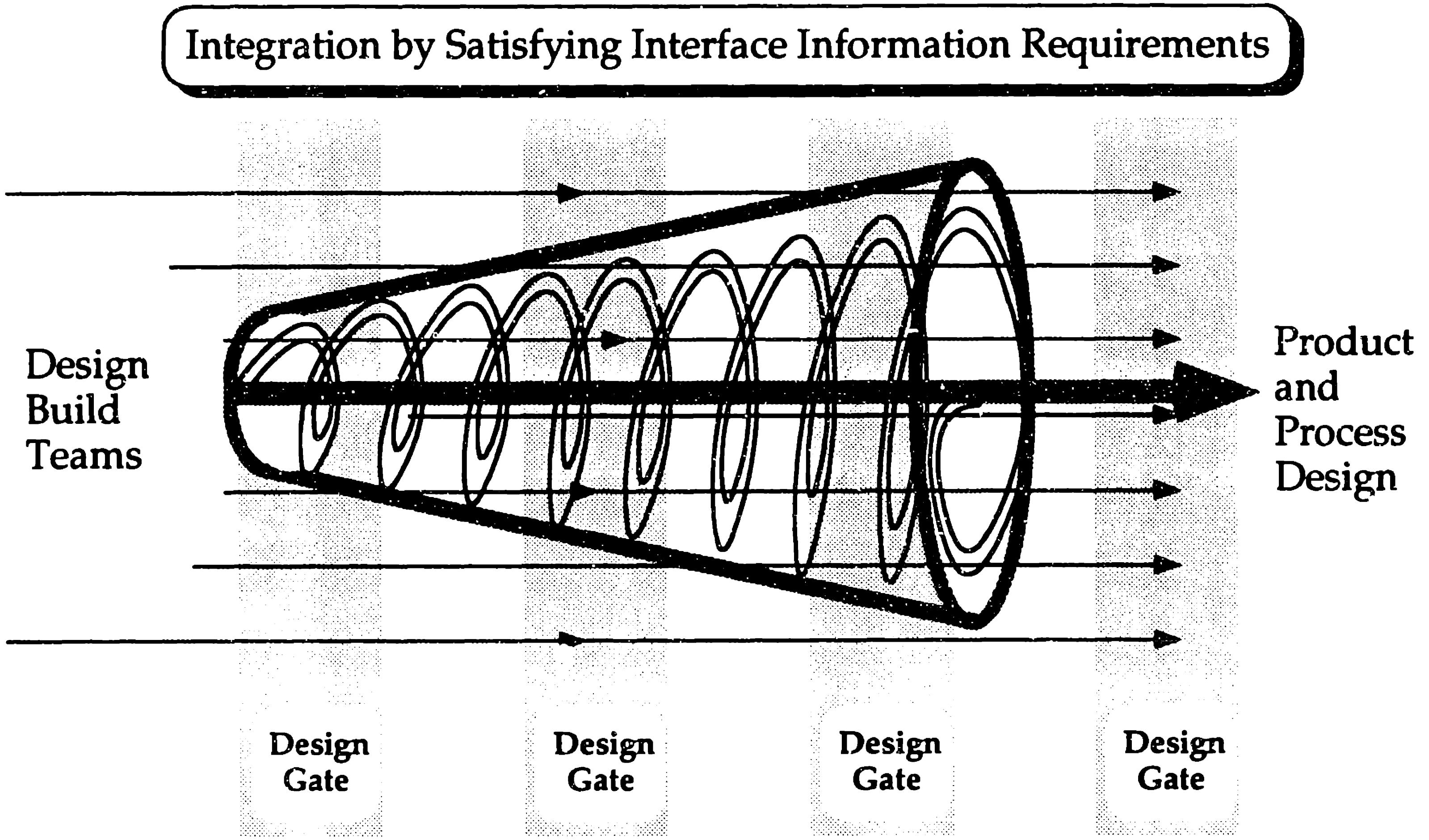
The proposed PDCA model would incorporate several of the concepts discussed in this chapter, as well as many of the processes currently in place on the 777, including:

- Integrated schedule based on interface information requirements between design groups;
- Evolving design freeze concept, with the ability to freeze critical attributes within the data model;
- Use of the PDCA cycle for each bit of interface information received and processed during a design iteration;
- Customer requirements used to drive the design;
- Team-based design concept;
- Periods of complete design freeze for large scale efforts of integration, such as the design stage reviews on the 777; and
- Computer-aided design tools used to accomplish the design integration of the product and process.

Where as the current design build process for the 777 was a parallel process with periods of integration (as shown in Figure 2.2), the proposed PDCA model would be an integrated approach to concurrent development. The PDCA model is more accurately depicted as a spiral representing the continuing integration and evolution of the design. Figure 4.10 shows this "spiral of quality" along with the periods of full scale integration necessary for project monitoring and control.

Figure 4.10

Integrated Design Definition Process Based on Interface Information Requirements



4. 7 Computer-Aided Integration of Product and Process Design

An organization's ability to integrate all aspects of product and process design early, and often, is a key element to the true promise of concurrent development; to bring high quality products to the market quickly. Application of CAD has changed the complexion of integration and opening up new frontiers for improving the development process. It has become an enabler for the magnitude of information required by the model suggested above.

Product Design Integration

The application of computer aided design (CAD) has provided an important enabling tool for the integration of design. There has always been a need for the integration of a design. Obviously, if the substructure and subsystems do not go together, the product will never become a reality. As discussed in Chapter 2, the 777 program brought Boeing out of the age of paper and physical prototypes, into the world of digital "mock-up".

The role played by CATIA™ in the integration of the airplane design cannot be overstated. Problems, which would have haunted past production lines, were found on the computer mock-up during the early stages of the design process. The computer tool also helped eliminate many of the simple, yet expensive, design errors which have plagued past programs.

Even with its many successes, CATIA™ as used on the 777 presented a simplified view of the world. It presented and checked interference conditions on only the nominal design. The real world is not nominal. Variation of detail parts, system components, and assemblies is a reality of the factory. True integration must include the impact of process variation. That is, the product design must be integrated with the process design.

Process Design Integration

Design for manufacturability (DFM) is one of the many concerns facing a design engineer when designing a Boeing airplane. Within the company, this term has often been given a limited definition; designing parts which can be easily fabricated. In general, assembly has been relegated to a secondary level of concern. I suspect that this focus is because fabrication processes of one individual component are much easier to understand than the complexities of an assembly. Yet, it is the assembly of an airplane that is most critical for the company's success.

Boeing is not alone in their focus on the detail level of manufacturing. As Nevins and Whitney put it in their book:

> "Until recently, it was thought that at most it was necessary to consider only how each part was to be made (process selection). Now we know how important it is to consider parts and groups of parts during design, that is, consider assembly."[5]

They go on to suggest that developers should focus the entire concurrent design process on assembly itself because of the ability to force integration of many diverse and complex issues. Assembly should become the basis for design integration. As they put it,

> "The design of assembly sequence raises specific problems which no other design aspect does. We [believe]... consideration of alternative assembly sequences, normally considered very late in the process design, really belongs in the early stages of product design, where each can heavily affect the other." [6]

That is not to say that Boeing ignored the area of assembly. One of the primary approaches to assembly producibility was the process of accumulating lessons learned from past airplane programs to be applied on the 777. This effort was led by the manufacturing engineers, with total DBT participation.

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[5] Nevins, James & Daniel Whitney, et. al., *Concurrent Design of Products and Processes: A Strategy for the Next Generation in Manufacturing* McGraw-Hill, New York,1989, pg. 197.
[6] *Ibid.*

The documented lessons learned provided a menu of potential assembly approaches from which to design the process.

The lessons learned process provided an important framework for designing the 777 assembly process. By applying lessons learned from the past, Boeing is able to avoid using once-failed techniques or processes. However, it will not be able to find an optimal technique or process among alternatives. In order to design improved processes, engineers must have analysis tools of a more technical nature to help integrate the product with the process design.

If there is no data, there will always be room for interpretation and personal judgment. When selecting the "best" process for building an airplane, this can be a fatal flaw. As one engineer complained, "There is little commonality between preferred manufacturing processes. DBT members often could not represent their departments. Others in the department would change the approach after the DBT had decided on a direction. To aggravate the problem, different production cells have different manufacturing approaches (i.e. Wichita Division versus Japan). "

So what is the best approach to assembly processes? The answer, of course, is "it depends", because it certainly does depend. Sources of variation in the assembly process for an airplane come from

- Part or component variation
- Tool index point variation (worn tools, allowed slop, etc.)
- Mechanic dependent issues (access, skill, etc.)
- Part to tool orientation
- Assembly sequence
- Measurement and go/no go observation variation.
- Tolerancing errors

In traditional design, only "tolerancing errors" would have been considered during the design stage. To provide a truly integrated concurrent environment for product and process development, all potential sources of information must be understood and considered.

4.8 Requirements

In order to accomplish this new approach to aircraft development, several areas of improvement need to be made in the existing 777 design process including:

- CAD-based process development tools which allow technical analysis of assembly processes prior to final design.
- Further integration of product and process design using interface information to guide an integrated schedule and partial design release.
- Organization structure changes which increase the focus and integration of the design teams at all stages in the process, while maintaining design democracy and concurrency.
- Deployment of customer and technical requirements at each stage of the development process and in all organizations, not just product design.

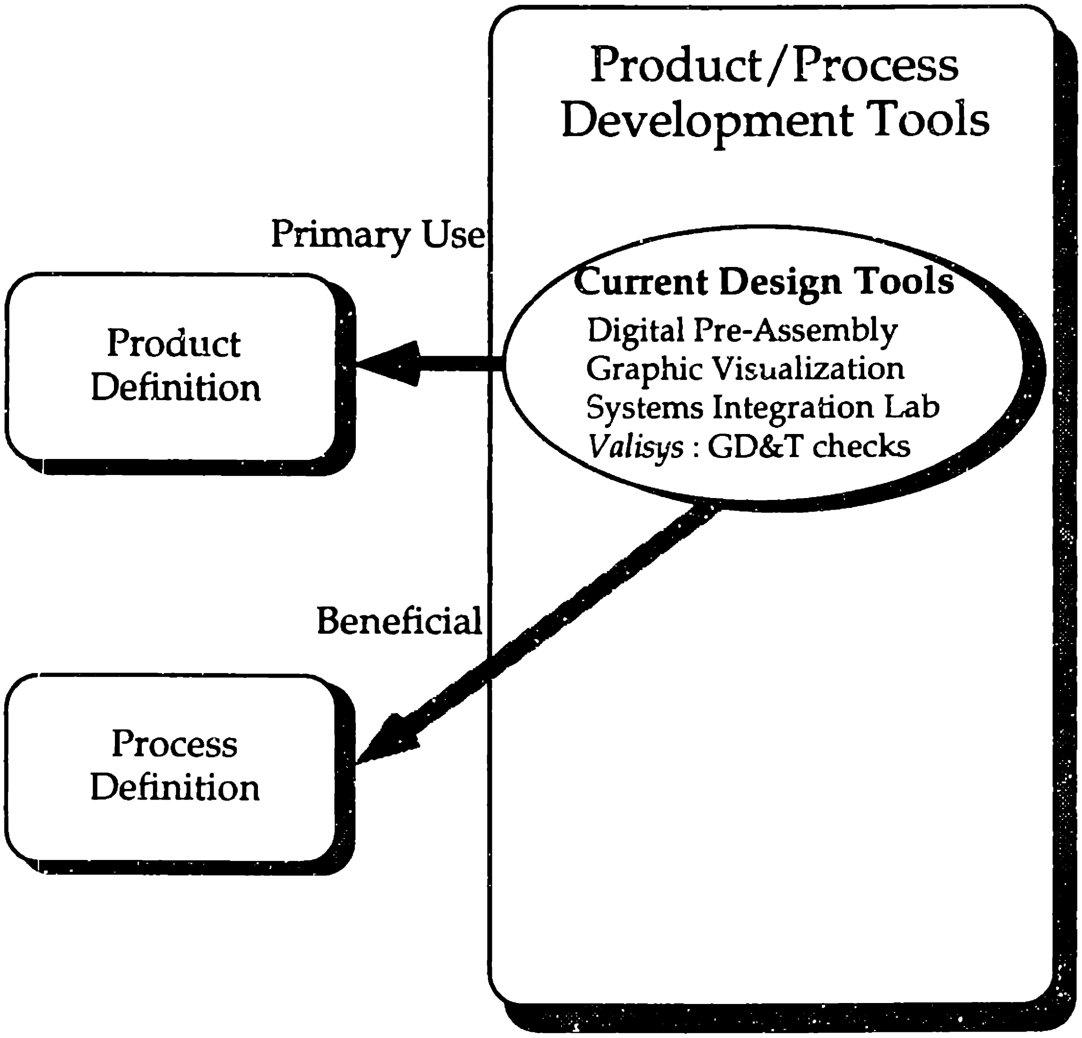
For the purposes of this document, I will address only the first requirement. In the next chapter I will propose CAD-based tools which will begin to provide information about the integration of product and process design. This will allow DBTs to select the best possible assembly process, taking into account variation, assembly sequence, and tooling index concepts found in the real world.

5. Assembly Process Development Tools

5.1 Proposed tools for assembly process development

As discussed in the previous chapter, CAD tools being used at Boeing have provided a means to technically, and unambiguously, check nominal designs for interferences and functionality. This provides the type of product design (subsystem to structure etc.) integration important to concurrent engineering. However, there are few such tools when it comes to analyzing the assembly process and integrating process with product design. As indicated in Figure 5.1 existing CAD tools are targeted toward product design.

Figure 5.1: Role of Current Development Tools in Product and Process Definition



On the 777 program, CAD solids data were used to visualize part geometry in order to improve process design. While not underestimating the value of looking at a 3D picture to help design an effective process, I do not believe that this tool provides the technical rigor necessary to find the "best" process in a real, variable world.

It should be noted that the CATIA™ system at Boeing was used to design production tooling for the 777. By incorporating CAD production parts into the CAD tools, designers could begin to see how the two could fit together in the nominal state. In a few locations, such as in Wichita, this formalized approach helped improve the design of both product and assembly tools.

Looking at the solids design of parts and tools (and how they fit together) is still not enough to move to the next level of process integration. Any effective assembly process tool must be able to incorporate the impact of the many sources of variation emanating from its use, and provide a simple, yet rigorous, test as to whether the assembly process will work.

Therefore, I believe that new software tools are necessary for the effective evaluation of the assembly process, including:

- Assembly sequence network tool

  Graphic-based system which registers assembly sequence and dimension links, plus develops assembly precedence network and component parts tree.

- Assembly animation

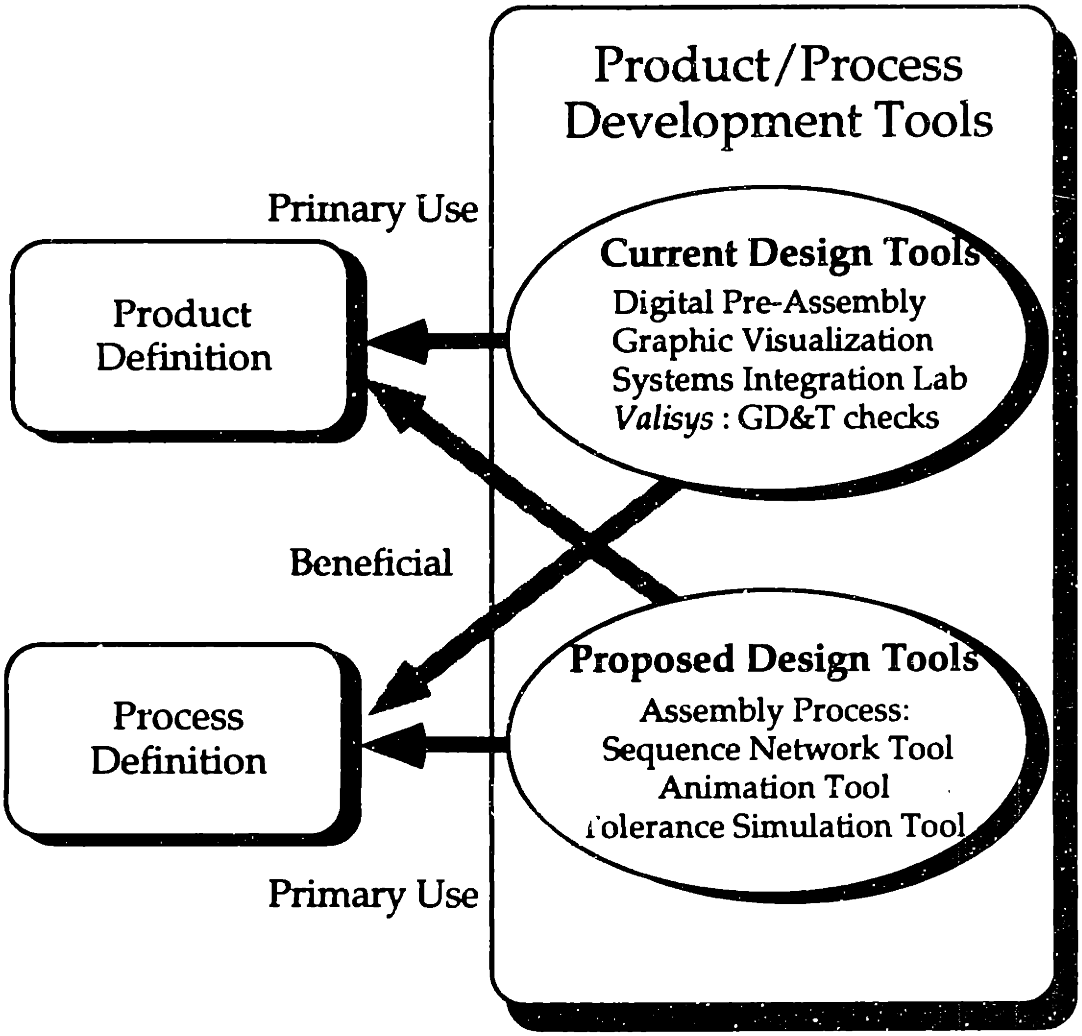
  Capability to recreate the assembly of the airplane in real time, based on assembly sequence and tooling concept.

- Assembly variation simulation

  Capability to simulate the effects of part to part variation, assembly sequence and the tool indexing scheme.

Figure 5.2 shows the role these proposed tools will have in Boeing's product and process development environment.

Figure 5.2: Role of Proposed Development Tools in Product and Process Definition



The proposed design tools will become an important part of the process definition for the airplane. They will also provide valuable (beneficial) information for those designing the product. Hopefully, with this more complete set of available analysis tools, the product and process design can be optimized as an integral package. Below I discuss the proposed software tools in more detail after reviewing some underlying concepts of assembly process analysis.

5.2 Technical Building Blocks for Assembly Process Analysis

A critical capability in the analysis of assembly processes is the ability to track the relative locations of numerous parts coming together to complete an assembly. In a nominal, as-designed assembly, the location of each part can be described in terms of their relationship to the global coordinate system. The component parts are located so they fit together, by design.

Reality isn't as favorable. If we are to simulate the actual location of a given part after the impact of variation has been introduced, a method must be put in place to provide a scorecard for deviations from the nominal design location for any given point on any given part. With this scorecard, the "stack-up" of variations introduced in parts, part-to-tool coordination, and tool indices can be identified and the impact on final assembly quality evaluated.

In his LFM thesis in 1992, Dari Shalon introduced a concept to handle the permutations caused by real-world manufacturing variations. His approach, titled Indexed Pre-Assembly with Variation (IPAV), provides a way to show the impact of differences from nominal dimensions[1]. There are three "building blocks" associated with this methodology:

- Local index point coordination systems;
- Dimension links between mating surfaces; and
- Notation to describe dimension links and assembly sequence.

The IPAV approach is presented in Appendix II using an example assembly to demonstrate the methodology.

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[1] Shalon , Dari, "Indexed Pre-Assembly with Variations; A Method of Representing Variations of Parts and Tools in CATIA", MIT Leaders for Manufacturing Program, Masters Thesis, June 1992.

Key Learning from IPAV

Evaluating an assembly using the IPAV methodology points out several important points which complicate the design of assembly processes. First, the assembly tool must be included in the variation stack-up analysis. When analyzing an assembly, it is not sufficient to consider only the component parts. Variation occurs in the process of fitting parts into the assembly tool. Therefore, the tool in our example is tracked using the same methods as components.

The tool must become an integral part of the assembly. In reality there is no difference of treatment in our analysis between tool and component part. The only difference is that the tool does not become a permanent portion of the assembly (the parts are not permanently fastened). It might be noted that the variation of the assembly tool can take two major forms; 1) Deformation of the tool itself, or 2) Index point location differences due to slop or built-in adjustments. The first case, caused by temperature differences or major induced strain (i.e. dropped tool) would be insignificant in most cases from assembly to assembly. However, the variation inherent in the indexing method of the tool could affect the assembly dramatically.

Secondly, assembly sequence of the components into the assembly tool impacts the final "as-built" configuration. As Appendix II indicates, the order in which components are located to the tool or to each other will result in different final results. Our method must include the assembly sequence as an important part of the design information.

Finally, variation in the component parts must be considered in the assembly analysis in order to understand the interactions between component parts, tooling, and the assembly sequence. These entities are intertwined, any analysis based only on a partial set could lead to sub-optimization in the design of the assembly process.

5.3 Description of Proposed Development Tools

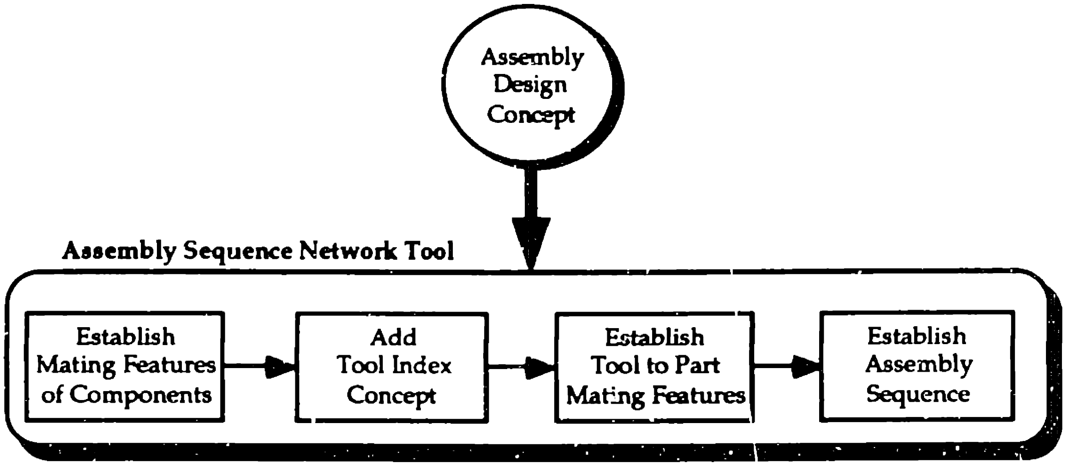
Assembly Sequence Network Tool

As I discussed above,the issue of sequence in the analysis of an assembly process cannot be overlooked. If the assembly sequence is so critical to the final outcome of the assembly, why are records of the established sequence kept separate from the geometrical record? The primary reason, of course, is historical; the design system is under the auspices of the design engineering function, while the manufacturing engineering organization "owns" the assembly sequence. In addition, the establishment and identification of assembly sequence can not be included in the current CAD system. A new software tool is necessary to finally bring the design together with the assembly sequence.

In order to perform further process design analysis an assembly sequence must be established by an engineer and recorded within the computer. I propose that an Assembly Sequence Network Tool be developed to perform these functions.

This graphics-based system would allow the user to establish a precedent network for a given assembly. Once established, the network will be utilized in subsequent process analysis, as well as used for assembly planning. A second product of the sequence tool will be a complete (and integrated) component parts tree for the assembly in its "as-built" configuration.

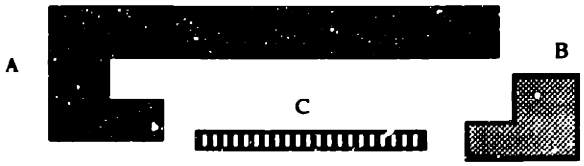
Selection of an assembly sequence is hardly a new task. Of course, sequencing of components into assembly tools is discussed by manufacturing and tooling engineers, if not documented explicitly. Early in an airplane development program, the higher-level assembly plan is contained in what is called the manufacturing plan (a six volume paper document on the 777 program). Later on, work instructions are currently used to convey the sequence at a more detailed level, but without a clear precedent path established. An assembly sequence network tool will provide an interactive method for establishing this sequence.



The basic input to the sequence tool is a 3D solids design of an assembly. For the purposes of establishing a sequence, the level of design definition can be quite low, possibly even in the conceptual, block stages of a design. After import of the design to the system, an "exploded assembly" view would be created to allow easy access to components and component features.

Nominal Assembly

Exploded View

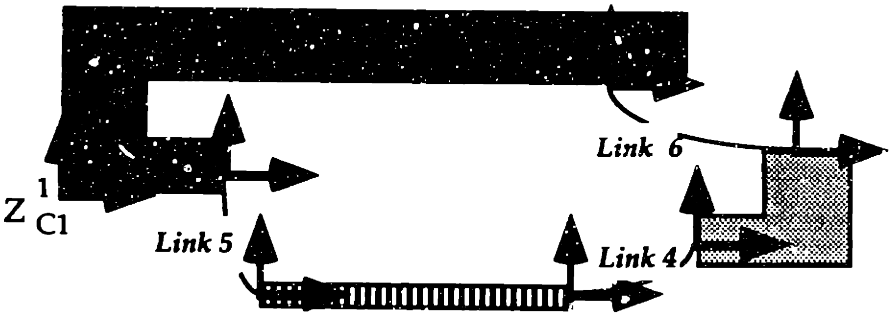


Establish Mating Features of Components

When an assembly is designed, there is no explicit identification of which surfaces on a given component mate with surfaces or points on other components. The design simply places individual component geometry at locations (with respect to a global coordinate system), which happen to be in close proximity or superimposed on other component geometry.

In order to accurately analyze the process, actual links between surfaces or points on mating components must be established. This task will establish the dimensional links discussed earlier in this chapter. Local index coordinate systems are linked to each other in a way which allows the evaluation of the dimensional stack-up of the assembly.

A graphic-based sequence tool will help ease the process of establishing the mating features. The tool will allow the engineer to "point and click" on component surfaces to establish the root of the link, then "point and click" on the mating surface to complete the dimension link. Within the computer, a link will be established which superimposes local indices on the surfaces when in the nominal case.

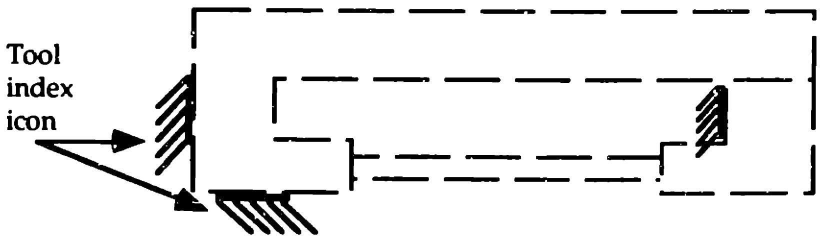


Add Tool Index Concept

The next step is to include the tool index concept in our analysis. An index concept provides a skeleton of how the assembly tool will function. Surfaces to be indexed (held in place) by the assembly are identified by including a geometric block in the location to be used in the tool. The only surfaces of interest in the tool at this point in time are the surfaces which mate with the component parts themselves. In addition, dimensions which have been designated as a "key characteristic" by the DBT can be marked for reference.

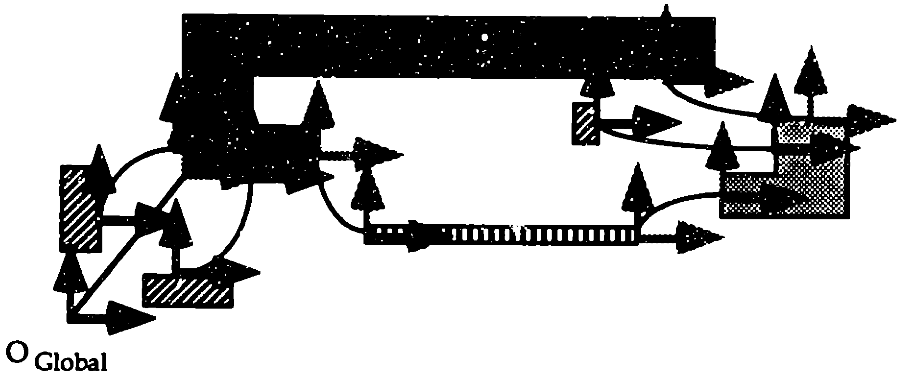
To accomplish this step, the sequence tool will allow the engineer to place an "index icon" at a specific position in the 3D design. This indicates that the tool will be mating to the components in that position. As indicated below, the index plan would appear in a separate ghosted view of the initial design geometry.

Tool Index Plan



Establish Tool to Part Mating Features

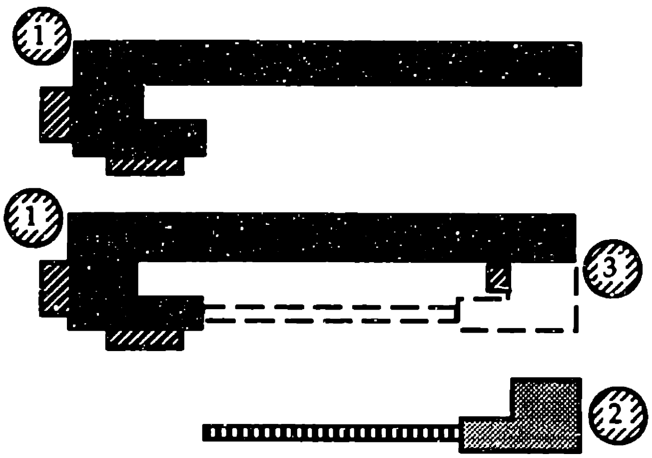
Since the tool is treated as a component, links between parts and tools must be established. However, since the computer understands that the tool index icon will mate to surfaces, the link between the component and the tool will be established in the computer when the index is established. To finalize the link, the engineer will simply highlight the component surfaces used for indexing.



Establish Assembly Sequence

Once the links have been established to help the computer assemble the design, the sequence in which the parts mate with each other must be established. This is accomplished by using the graphic user interface to pick component parts to establish the sequence. Obvious relationships (i.e. the first parts picked must mate to the assembly tool) can be programmed in a rule-based manner to provide immediate feedback to the engineer.

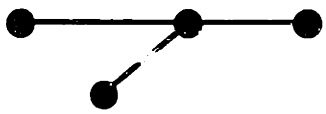
The engineer will select a component part to be assembled first by "pointing and clicking" to highlight the part. The computer would respond by translating the part from its "exploded assembly" location to the location corresponding to mating parts and tools. Each successive selection by the engineer will be recorded in a precedence network. Again, it is important to note that the relationships of part-to-part and part-to-tool mating features are stored in the computer and used to establish the location of each component relative to others.



Assembly Sequence

Step 1: Locate part A
Step 2: Attach Tube C to Connector B
Step 3: Locate Assembly using tool 2 and attach

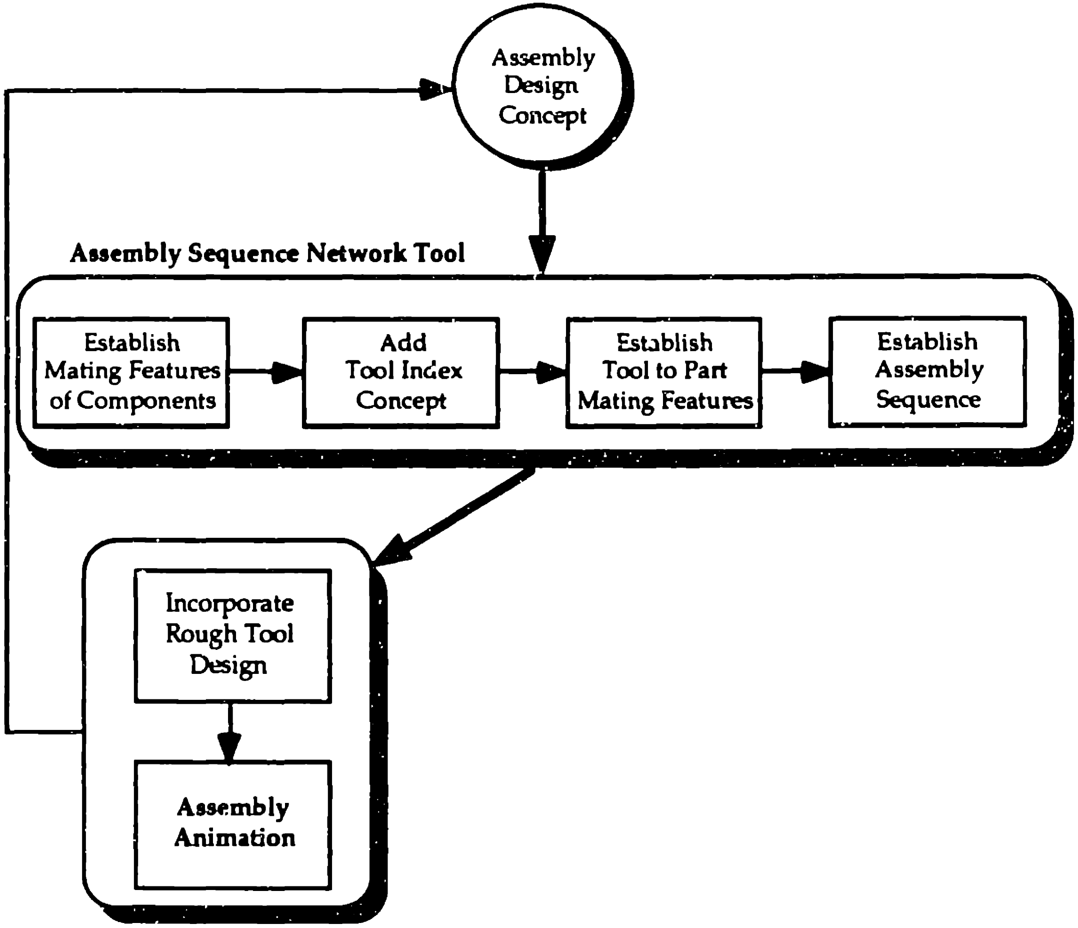
Precedence Network



The precedence network information and the assembly sequence instructions developed as part of this exercise can now be modified for use in a variety of shop floor control and production information applications.

Assembly Animation Tool

Once the order of assembly, the tool index concept, and the dimension chains for the assembly have been established, the analysis of the process as designed can begin.



An assembly process is simply the combination of tooling concepts, assembly sequence, and component parts; plus a few other factors of interest, such tool usage, access for assembly, ergonomics, and safety. Just as with product design, the process is much easier to evaluate and analyze if it "comes to life". That is, using graphic visualization techniques to provide a view of what the process of assembly will look like.

Assembly from a product design standpoint concerns the relative location of component parts in the nominal condition. This is an assembly product as-designed. Process designers are more interested in what component location relationships look like after the product has been assembled by the process. This configuration is considered to be as-tooled.

Using the relationships of mating surfaces established using the sequence network tool, the as-tooled configuration of the nominal design can be determined. This is accomplished by simply "building the assembly on the screen." Component parts are located within the tool based on the established mating relationships. Quality of the finished assembly depends on the effectiveness of the tool index concept, the sequence of assembly, and the product design itself.

The first step in this stage is to incorporate a rough description of the tool design which goes beyond the tool index scheme used above. This rough tool design should include conceptual geometry so that usage and access issues can be evaluated.

Finally, the process design can be evaluated using computer-generated animation. The proposed animation tool would use graphic visualization technology to allow the engineer to see the results of his/her process design. After selection of the product and process design (including dimension links, assembly sequence, and tool index plan), a single stroke will begin the "motion picture" of the sequenced parts being placed in a tool until the assembly is complete. However, this would be more than just a pretty picture; the assembly just developed on the screen based on the process would then be evaluated using the interference check tools available in the CATIA™ system.

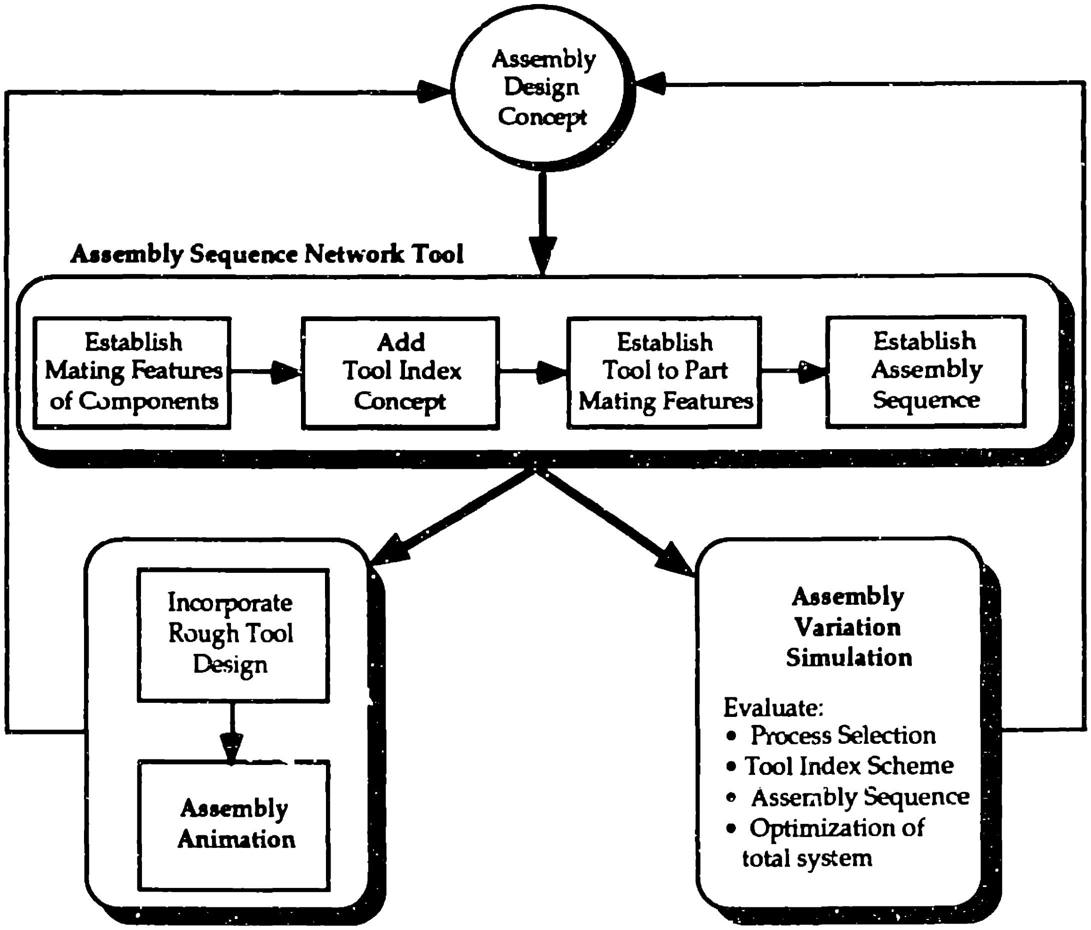
Several aspects of the process design can be evaluated using this process:

- Is there adequate access for the mechanic to use the tool as described?
- Does the as-tooled assembly meet the function requirements set forth by the customer through the DBT?

- Are there more efficient assembly sequences or tool designs resulting in the same assembly?
- Are there any obvious product design/process design incongruities, such as tool interferences with components or part interferences?
- Could smaller or fewer tools be used to accomplish the same task?

Assembly Variation Simulation

The limit to assembly animation is that it is, just as with the product design, based on nominal dimensions. Further analysis using assembly variation simulation will allow the engineer to check the design based on the reality of variation.



As proposed, this tool will analyze the process design by incorporating variation in the dimensions related to component parts, part-to-part interfaces, tool-to-part interfaces, and tool index points. The engineer would describe the sources of variation through an interactive session prior to the simulation. Each component part, interface, and index point variation will be approximated using a statistical distribution and an estimate of central tendency and spread (i.e. mean and standard deviation for a normal distribution). The system would provide a simple way to select the appropriate distribution or go to a default, such as normal or uniform.

Once each of the potential sources of distribution have been identified with a distribution (or purposely ignored for the analysis), the simulation can begin. A Monte Carlo random number simulation will be run to provide numbers associated with each of the dimensions being varied. With each iteration, a new assembly is "built" in the system. Results of each iteration, measurement of a critical dimension on the assembly, are recorded. A run of 100 or so iterations will provide an accurate picture of how the assembly will work in the real world. Of course, the simulation is only as good as the assumptions used in its development. However, even with educated guesses of process characteristics, the effectiveness of the process design can be easily gauge.

Final results of a simulation will provide the engineer with valuable information:

- Average measurement of the critical dimension.
- Distribution of the resultant dimension.
- Process capability of the assembly process based on design tolerances for the dimension in question.
- Percent of the time rework or scrap will be necessary.
- Possibly a "loss function", which calculates the cost per part for each deviation from the nominal value.

- Total quality cost for the process based on costs of rework and scrap (a total cost analysis, including capital costs from tool, process time, etc.) may also be beneficial.

It is now time to use the simulation tool to perform a "what if" analysis by changing various aspects of the product and process design. For instance,

- Process selection for components could be revisited to reduce the variation associated with a given dimension.
- New tool index schemes may be tried to reduce the effect of variation.
- Changes could be made in the product design based on design for manufacturing rules, such as reducing part count, as a way of reducing the impact of variation.
- Different assembly sequences can be analyzed to ensure the most effective, as well as the most efficient.
- Reductions in the amount or "beefiness" of tooling could be analyzed to determine if less costly alternatives could be utilized.
- Previously selected key characteristics on component parts can be validated so that proper process control can take place.
- The impact of changes in material can be easily analyzed with a run of the simulation.

5.4 757 Sill Assembly Example

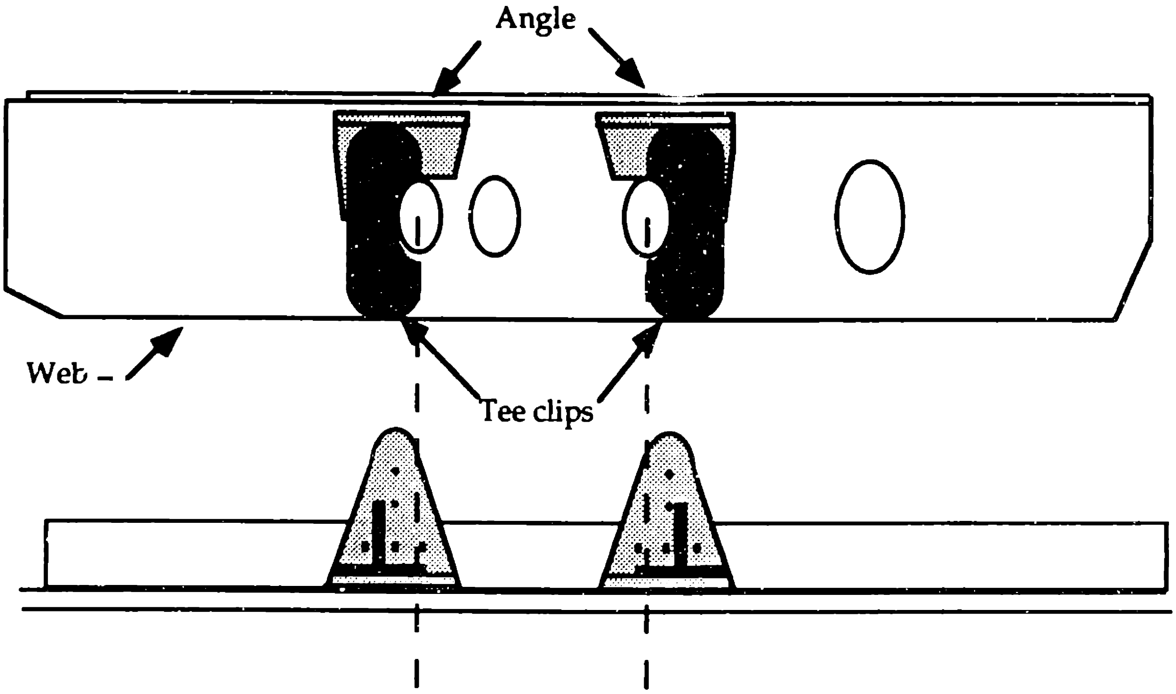
In order to describe more fully the purpose and function of the proposed development tools, a sample assembly was selected for a prototype demonstration. The example used is a very simple assembly: an escape hatch sill assembly for the 757 overwing exit airplane. Production of the assembly is in the Renton Division Lot Time shop, where it has been produced since

1981. It was selected because of its limited component parts, the central role the tool plays in the assembly, and a recent spate of rejections of the part after many years of production. For clarity, a few components were left out of the analysis.

Below is a representation of the assembly. It is composed of five components;

- 1 web
- 2 angles
- 2 clips.

757 Upper Escape Hatch Sill Assembly
144N8621-923/924



The sill assembly is located in the upper portion of the escape hatch over the wing of the 757. After installation, the tee clips and angles are oriented upside-down. Mating systems and structure, used for the operation of the escape hatch in the case of an emergency, make the location of the components critical to the assembly's function.

3D Model of Assembly

The beginning point of our journey is a 3D solids model of the proposed assembly design. In the case of the sill assembly, a CATIA™ 3D model was created for the example, based on current engineering drawings for the assembly and components. A view of the 3D model can be found in Figure 5.3. This model was developed for this demonstration using available paper engineering drawings. In production use, a CATIA™ model developed for product design would be utilized during process analysis.

Component-to-Component Interfaces

Each component-to-component interface is identified by the engineer. Figure 5.4 shows a view of what the engineer would see on the computer screen. The computer establishes local indices at each mating surface identified. This will be accomplished using a "point and click" routine on the two subsequent surfaces (the fat arrow represents the mouse cursor).

Once all the interfacing surfaces and points are identified, the nominal assembly has been identified within the computer. In addition, dimension links have been established between each of the local indices, paving the way for further analysis. Each point identified as mating will be annotated using the notation system defined in Appendix II. That is:

$$Z^{n}_{\alpha/\xi}$$

A global coordinate system is established to be the reference for all the local indices.

Figure 5.4 View of Sill Assembly as Modeled in CATIA™

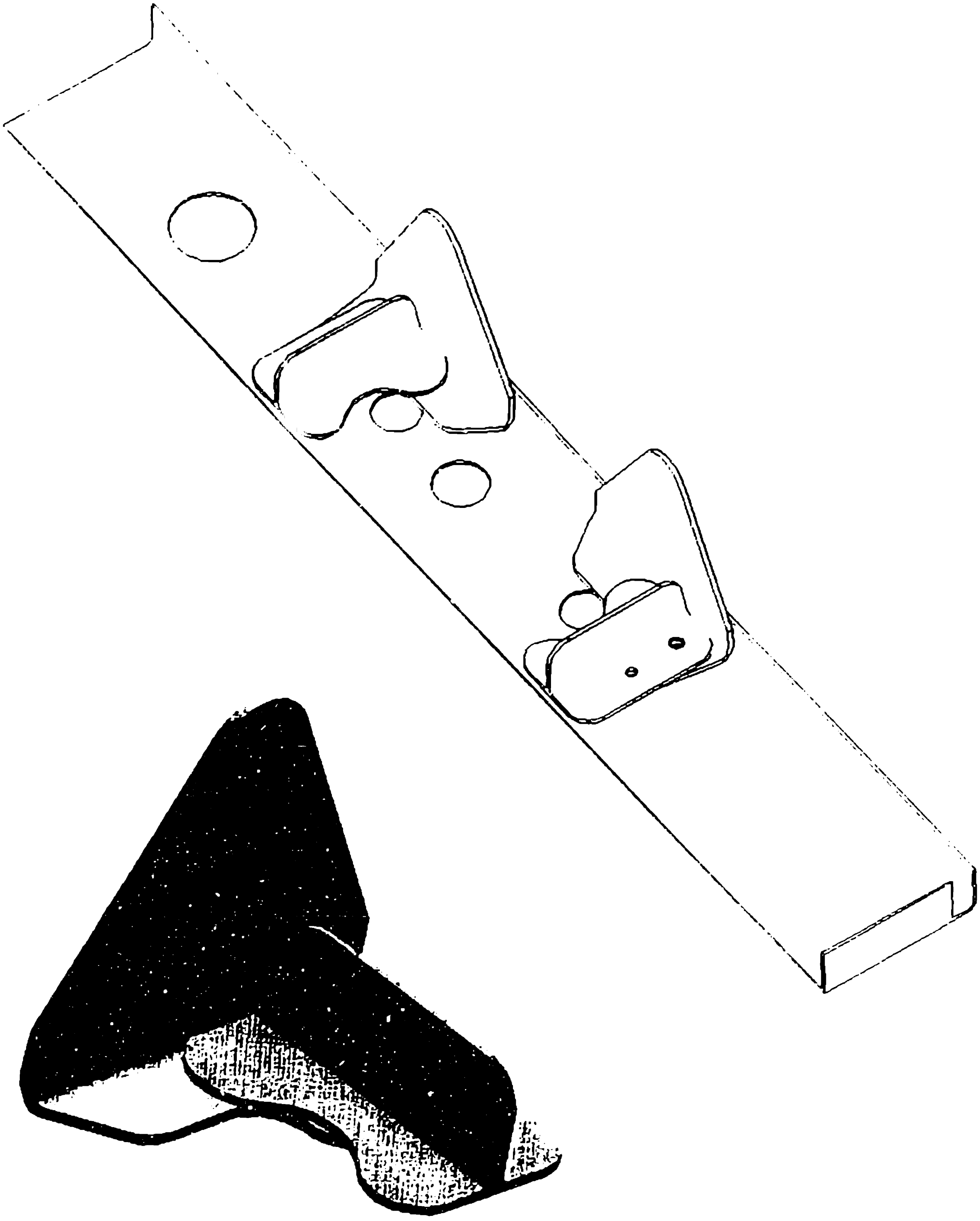
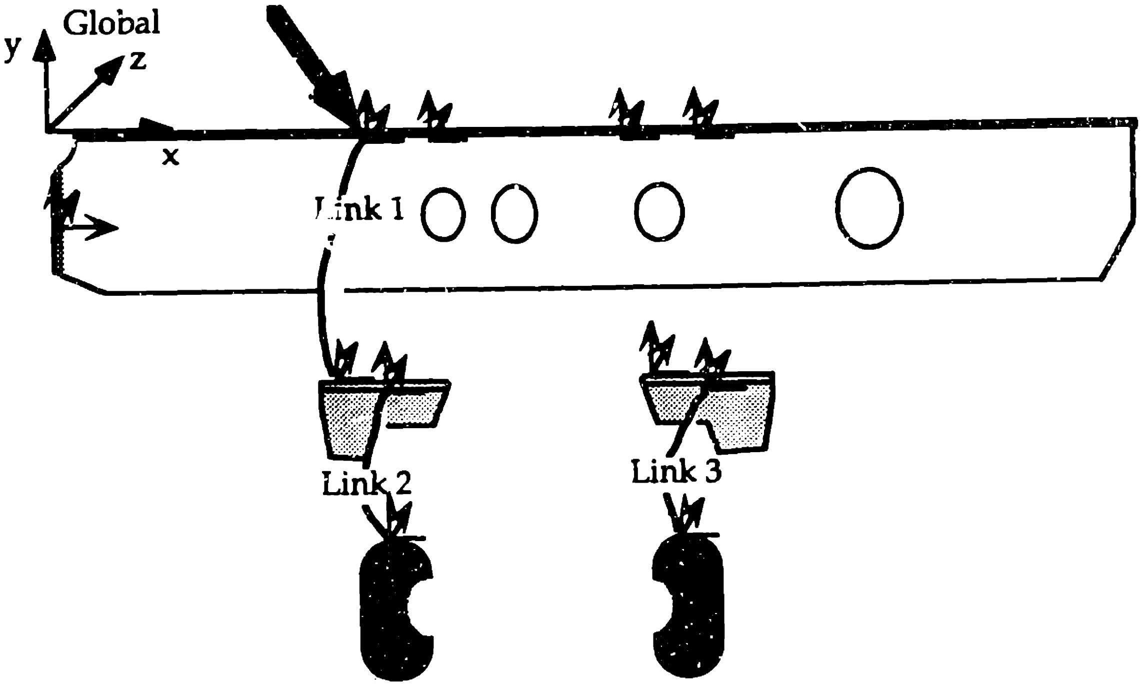


Figure 5.4
"Point and Click" to Identify Mating Surfaces



Establish Key Attributes and Tooling Index Concept

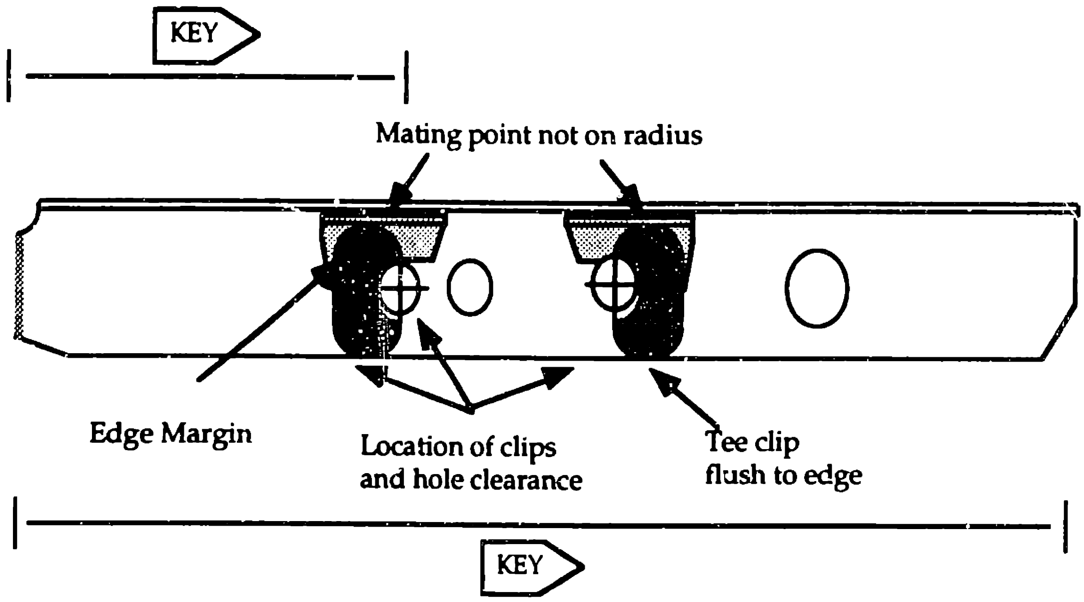
Key attributes (critical dimensions) of the assembly are identified and established within the computer. The attributes selected as key are important based on the function of the assembly and its interface requirements. Attributes considered key in this case include:

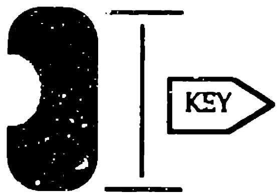
- Location of each clip relative to the edges of the web.
- Location of clips relative to holes.
- Clip cannot ride the radius of the angle.

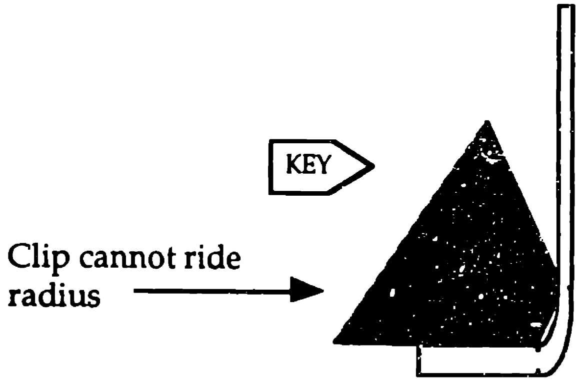
This leads to certain key characteristics for each of the components including:

- Length of the clip.
- Length of the web.
- Angle of angle.

Key Characteristics (Critical Dimensions)





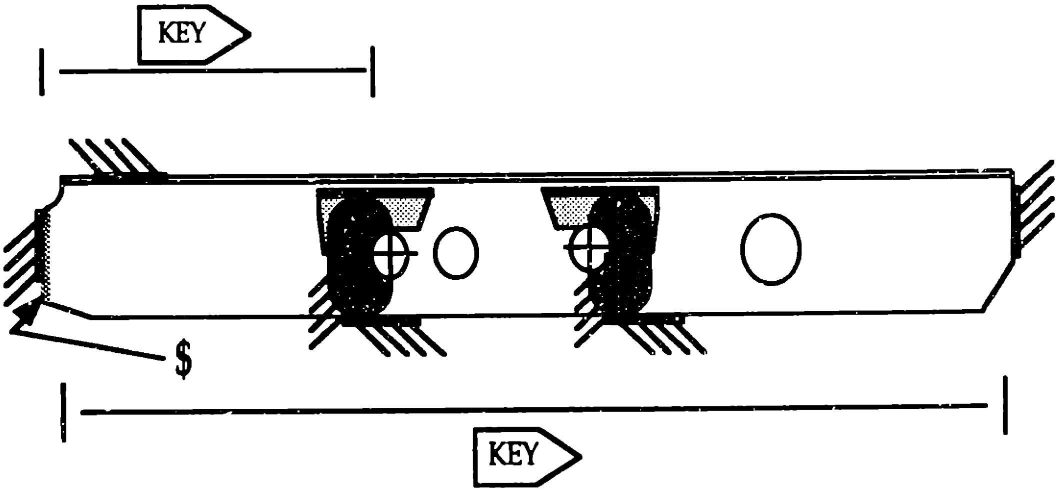


The tooling index concept for the assembly is then added to the analysis model. A tool index icon ▨ is added at locations which will become tool-to-part interfacing surfaces. Also included in the index plan is a reference or $ surface to which all other indices are related. The index plan is based on tooling concepts, such as the 3 point/2 point/1 point indexing scheme for locating components.

In this case, the index plan is based on the original tooling provided for the assembly. In general, this would be provided by the engineer or DBT as part of the development activity. The index plan includes:

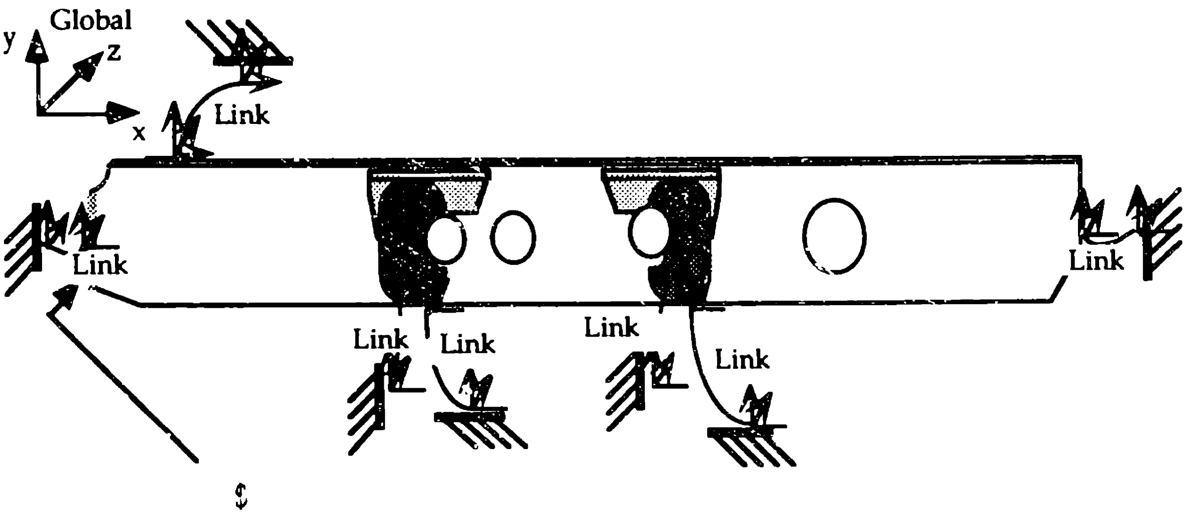
- Orientation of web.
- Length of the web (and a doubler with a mirror image flange).
- Placement of the clips, both relative to the end of the web and in relationship to the angle.

Tool Index Plan is Identified



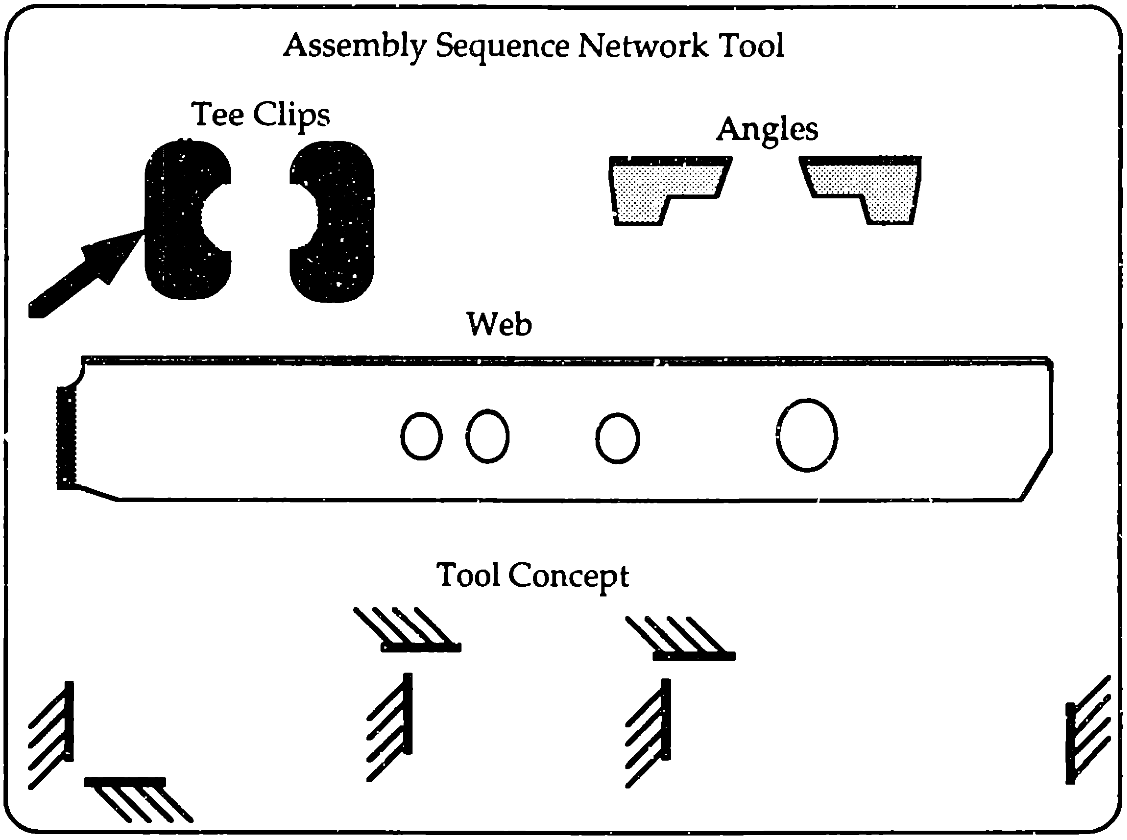
Just as with the component-to-component mating points and surfaces, the part-to-tool interfaces must be identified and linkages between local indices established. Since an icon was used to identify the index surfaces in the index plan, the computer can automatically establish local indices and make the linkages between parts and tools. In this manner, the tool index concept has become an integral part of the design. A global coordinate system (related back to a airplane global coordinate system) is identified and incorporated into the tool index design.

Links Between Tool Surfaces and Components



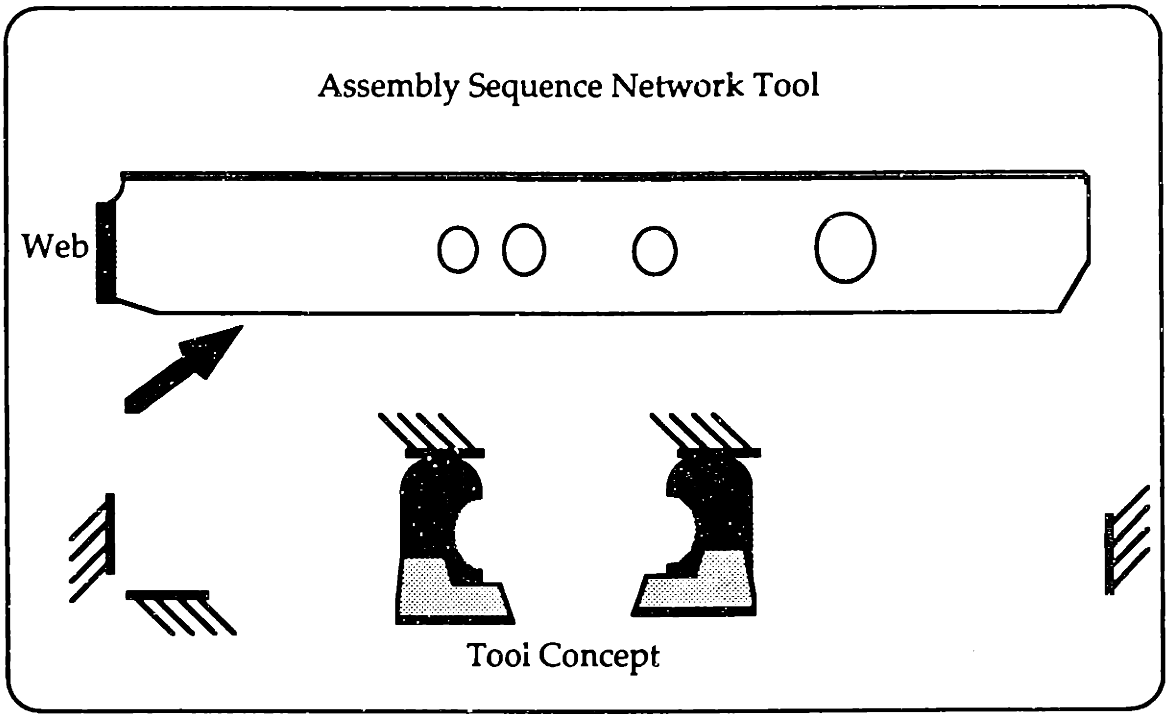
Establish Assembly Sequence

The assembly sequence is established using an interactive graphic session. The first component to be placed in the tool is selected, then the second, etc. Selecting the component is accomplished by pointing the mouse cursor at the component, then clicking to highlight. Since all the mating relationships between parts and tool have already been identified, the parts are able to "fly" into place after selection. This process continues until each of the components have been selected and "placed" into the assembly tool.

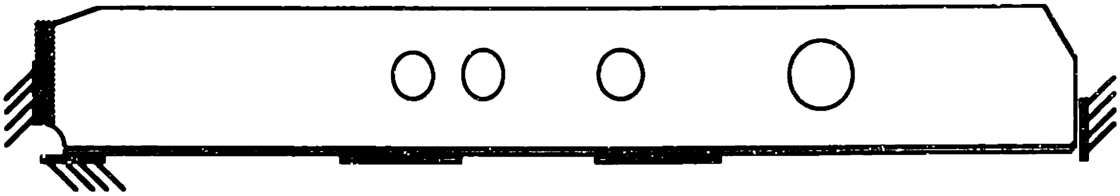


The assembly is built within the computer based on the relationships previously identified. It should be noted that by this time the engineer should have a concept of how the tool will be used. In this case, the assembly was built "upside-down" with clips and angles being loaded first. This replicates the actual tool design used for the sill assembly.

The process continues until all the components have been put in place. The result is the nominal assembly in the as-tooled configuration.



And finally, the assembly is completed on the screen.

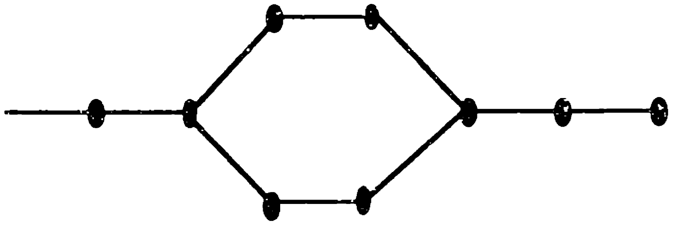


Information from Assembly Sequence Network Tool

At this point there have been two major results of the process; the establishment of an assembly precedence network and a component parts tree for the assembly. These data outputs can be used for downstream processing such as parts ordering, shop floor activity loading, budgeting, and inventory planning.

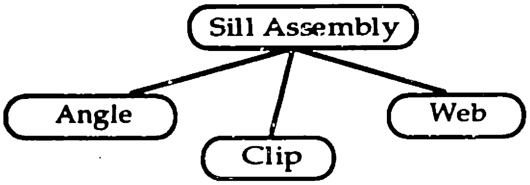
Precedence network

Precedence network is established depicting assembly sequence.



Component Parts Tree

Component Parts Tree is also recorded for use in other areas.



Assembly Animation

After the establishment of the assembly sequence, the interface links, and the tool index scheme, it is now time to analyze the complete process design. That is, it is time to evaluate whether the tool concepts and assembly sequence will work as designed to provide a quality assembly.

Before the assembly is animated in the computer, a rough tool design should be included in the analysis model to ensure a more accurate view of what the mechanics will have to face in production. In the sill assembly case, the actual production tool as designed (and equivalent to the current production tool) was modeled in 3D solids in CATIA™. Figure 5.5 shows a 3D solids view of the tool.

Animation can now begin. A press of a key or a point of the cursor can begin the animation process. Animation will allow the engineer to see the assembly being built on screen at any desirable speed.

Components are located per tool and with the orientation found in the actual part-to-part relationships. The final result is an as-tooled nominal assembly. While the tooling concept has been included in the model, no variation has been introduced. Figures 5.6 shows the tool with only the clips and angles in place. In Figure 5.7, the web has been added to complete the assembly.

Based on analysis of the assembly animation, the engineer can identify major problems with the current process design. Without changes to the process design and/or product design, the assembly process would result in a rejectable conditions (as was the case in this postmortem example). None of the problems could be found using digital preassembly (DPA) or any other analysis techniques which only analyze the as-designed nominal assembly. Problems identified with the assembly include:

1) **Access problem due to assembly sequence**
   By looking at the animation, it becomes clear that the assembly sequence has limited the access of the clip and angle. Since the interface between the clip and angle is one of the key attributes of the assembly, a visual check by the mechanic would be an appropriate procedure to prevent problems. The assembly sequence as proposed blocks the view of this critical interface.

Figure 5.5

Three Dimensional Solids Model of Assembly Tool

(Developed at Boeing in CATIA™)

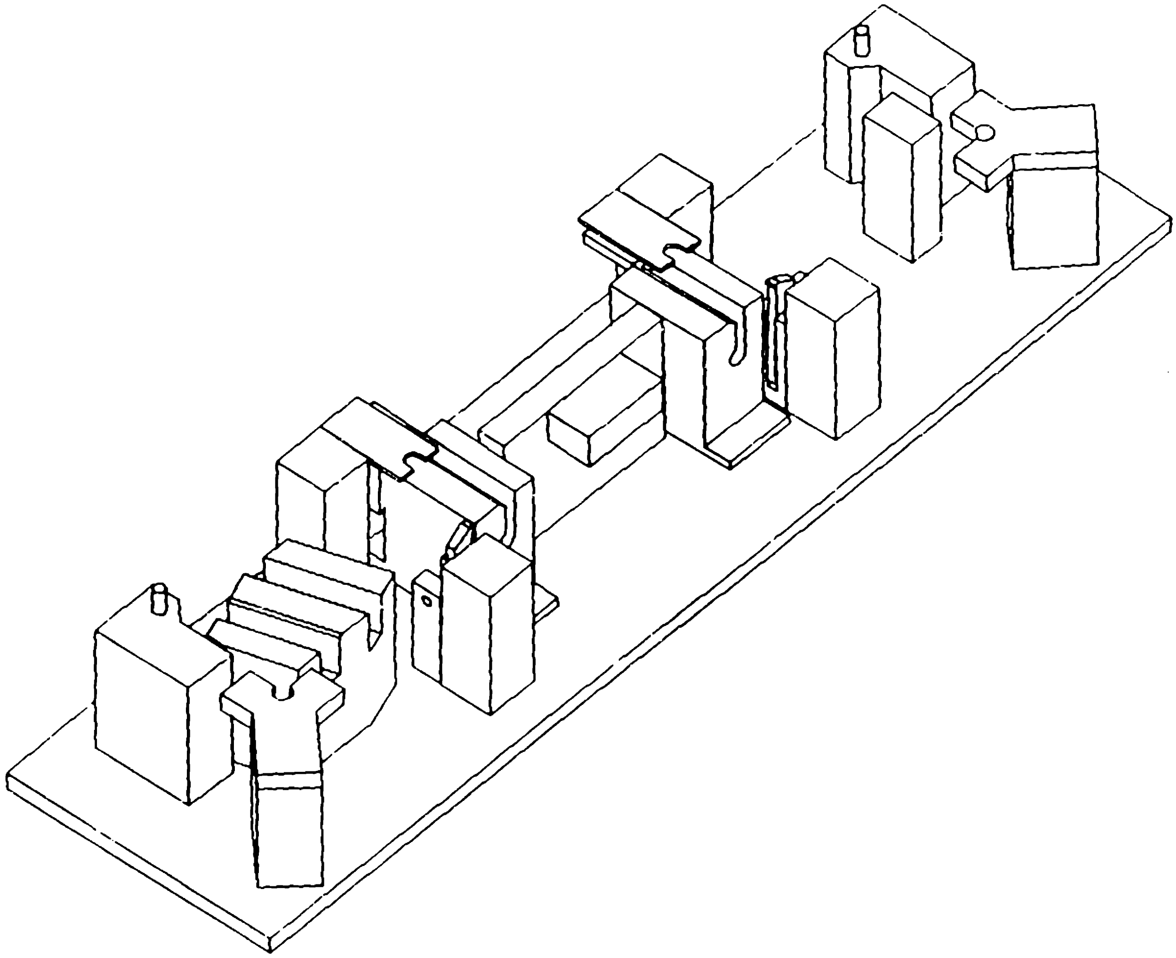


Figure 5.6

Three Dimensional Solids Model of Assembly Tool
Locating Tee Clips and Angles
(Developed at Boeing in CATIA™)

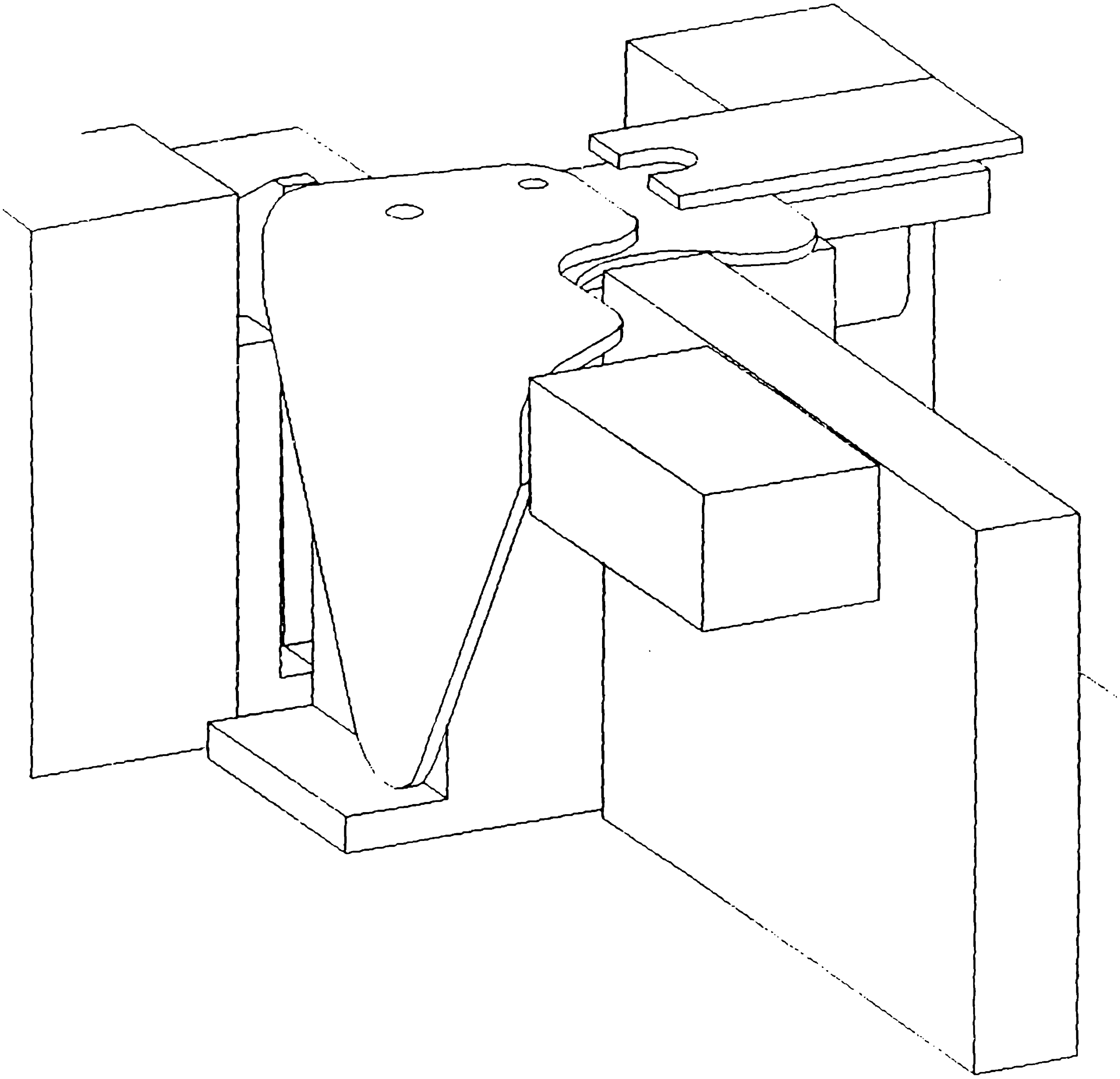
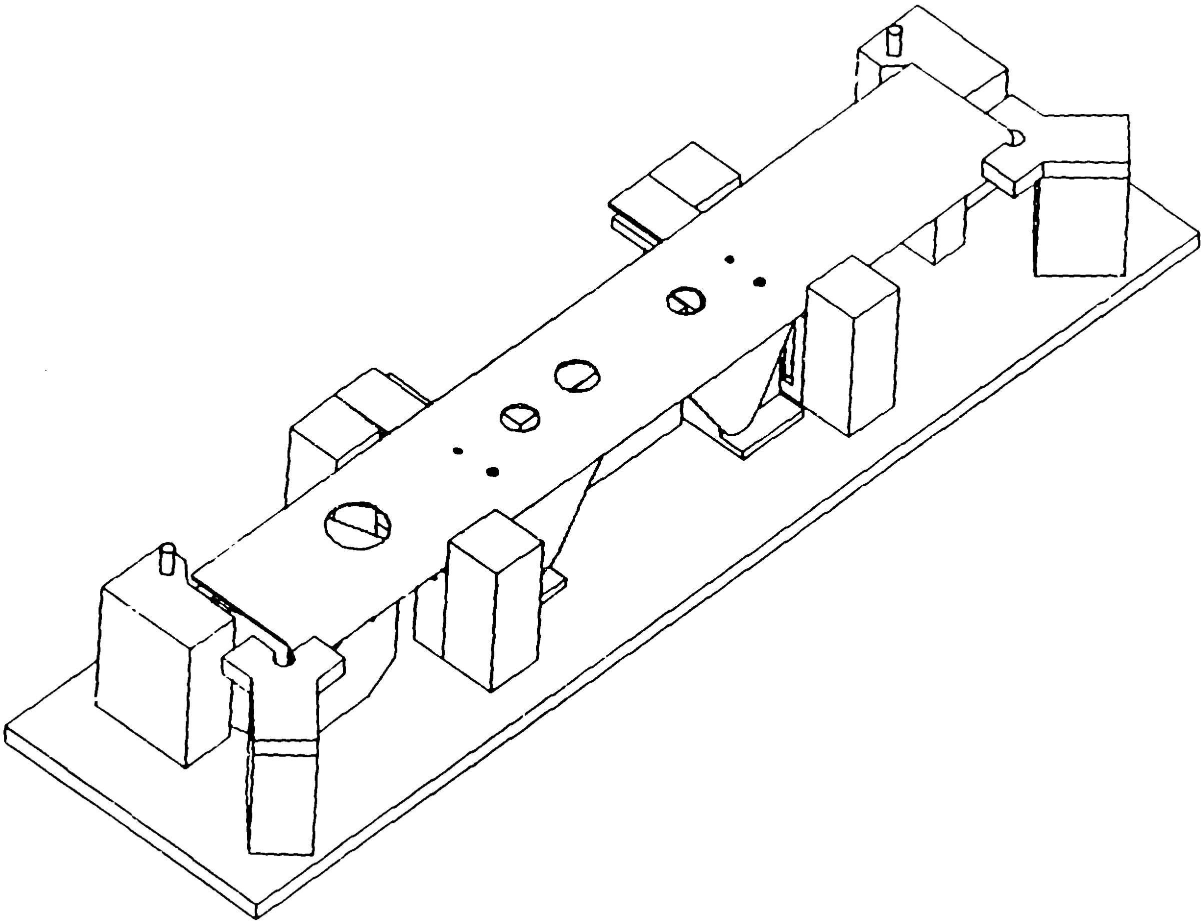


Figure 5.7

Three Dimensional Solids Model of Assembly Tool
With All Component Parts Located
(Developed at Boeing in CATIA™)



Potential Solution: A tool design which allows access to this area of the assembly would be best. Building the assembly "upside-down" or in a tool 90° to the table with an open base could provide this visibility.

2) **Tooling as designed interferes with angles**
An obvious error in the original tool design would have been easily found in the assembly animation. A flange on the tool interfered with the angles about an inch. This miscalculation was caught during the first production tool- tryout. While the rework to the tool (grinding out clearance) was rather minor, this type of error should have been caught in the earliest periods of tool development.

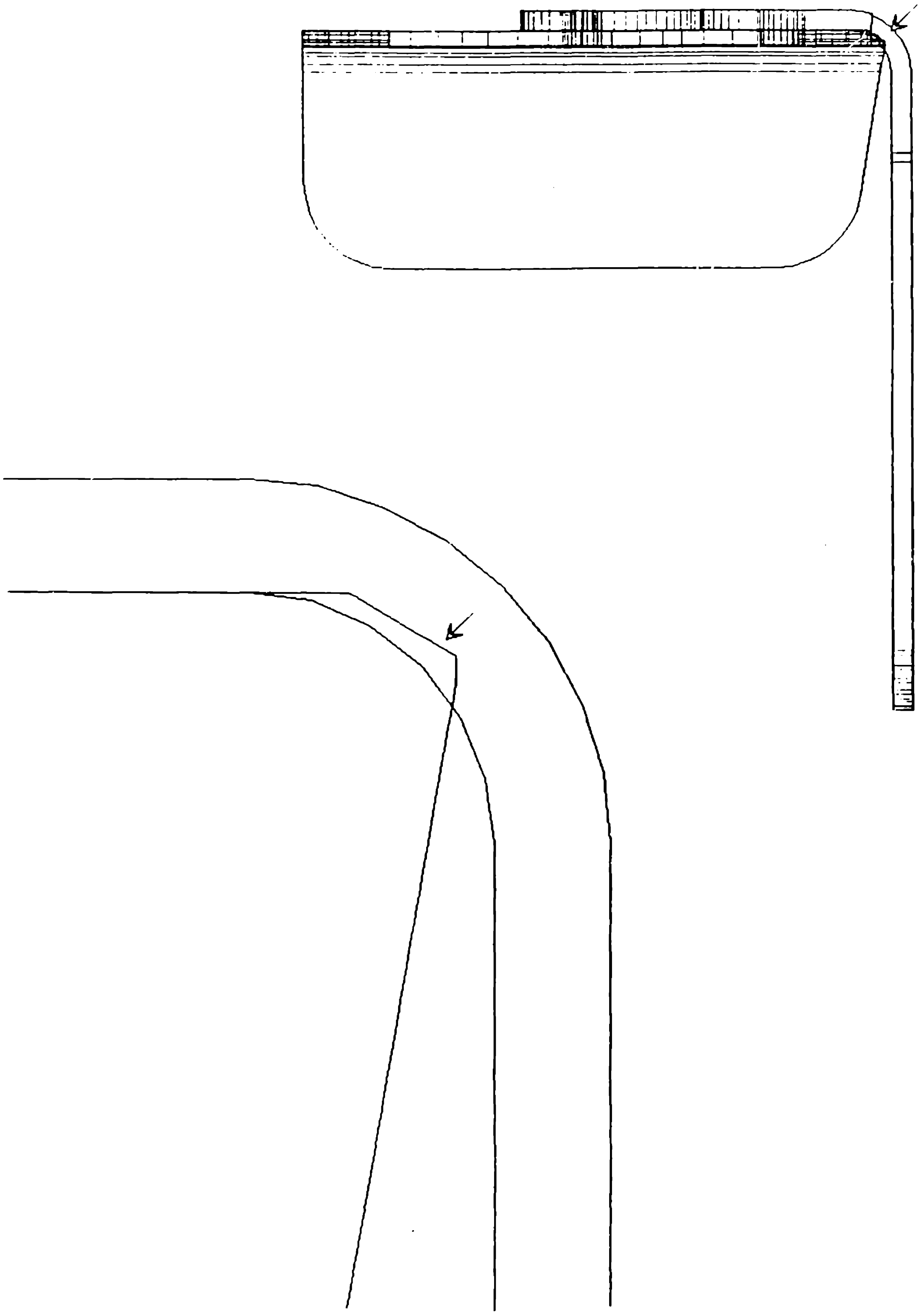
Potential solution: Redesign the tool to avoid interference.

3) **Interference in the as-tooled nominal assembly**
Detailed analysis of the as-tooled assembly revealed a .040" interference between the clip and the angle. This would have created a riding condition, even in the nominal configuration! The primary problem with the assembly had been found. The interference can be detected in the CATIA™ view shown in Figure 5.8.

Potential solution: Reposition the index point for the clip .050" away from its present location.

In each of the situations above, the problem would not have been identified using the traditional approach to digital pre-assembly. The assembly animation tool allowed the additional capability to check the as-tooled assembly in real-time, and in an animated fashion. In its current usage, DPA only looks for interferences between perfectly dimensioned and perfectly placed component parts. As we found in this example, reality is seldom this easy.

Figure 5.8
Cross-Section View of Interference Between Clip and Angle
(Developed at Boeing in CATIA™)



Assembly Variation Simulation Tool

The analysis of the nominal product and process design is complete. It is now time to introduce the effects of variation. Using this simulation tool, the impact of part-to-part and part-to-tool variation can be seen in a matter of minutes. Previously, the full impact of variation was proven only after several airplanes were produced.

First, the engineer identifies potential sources of variation associated with the assembly. A judgment is made as to the significance of the variation source. Those sources deemed critical to the analysis will require data to describe the character of their distribution in the next step. Sources of variation considered for study in sill assembly process might include:

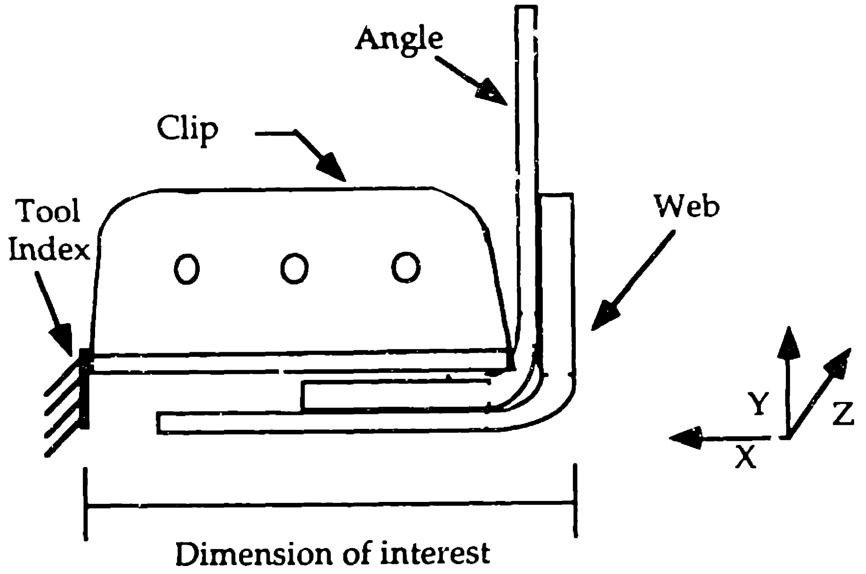
- Part or component variation
  - clip (length, material thickness)
  - angle (angle, material thickness)
  - web (length, width, angle, flange thickness)
- Tool index point variation
  - flexibility in tool index points
- Part to tool orientation
  - "play" in how angles fit into tool
  - Clip orientation against tool index point
- Assembly sequence

Build-up Study for the Sill Assembly

The next step in the analysis of the sill assembly is to determine which dimension(s) is of concern. In this case, the position of the clip, as placed by the tool index point, is analyzed relative to the angle. The interface between the angle and the clip is defined as a key characteristic of the assembly. Per engineering drawing, the clip cannot interfere with (or "ride") the radius of the angle. For purposes of our example, only the build up of the components in the X direction along the length of the clip will be analyzed. Of course, the actual computer simulation could analyze these relationships in three dimensions using matrix transformations.

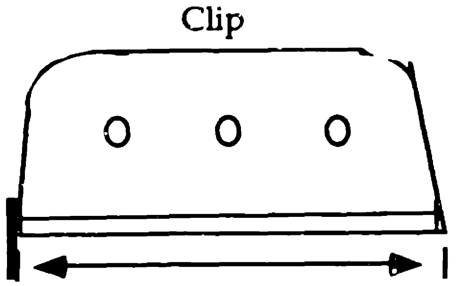
Below is a view showing the critical dimension and how the components and the tool index point interface.

Location of Clip Versus Angle in the X Direction



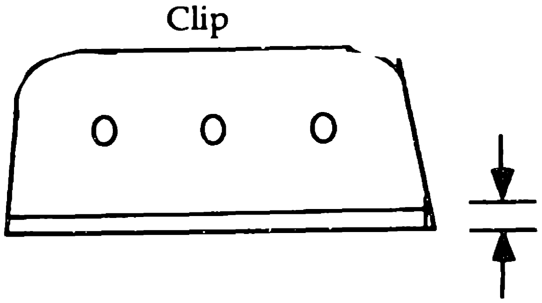
Dimensions critical to the assembly build-up in the X direction are determined for each component. For instance:

Clip Length



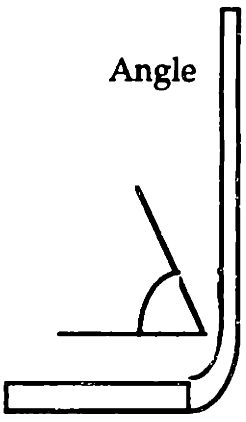
$$D \begin{matrix} Z^{1}_{1} \\ Z^{1}_{2} \end{matrix}$$

Clip thickness



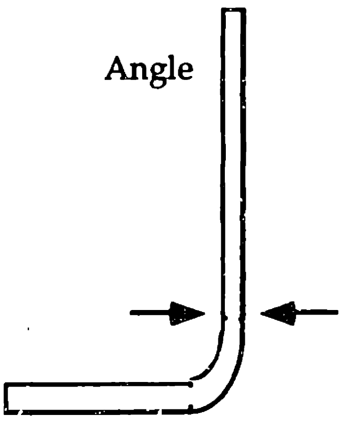
$$D \begin{matrix} Z^{1}_{3/1} \\ Z^{1}_{4/1} \end{matrix}$$

Angle Angle



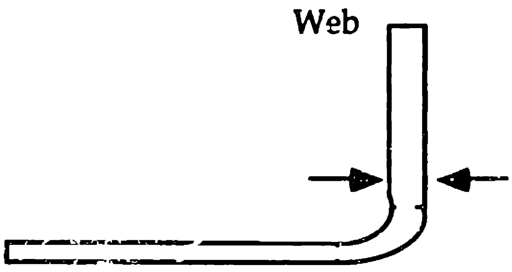
$$\measuredangle \begin{matrix} Z^{2}_{1/1} \\ Z^{2} \end{matrix} \text{ (Angle)}$$

Angle material thickness



$$D \begin{matrix} Z^{2}_{1/1} \\ Z^{2}_{2/1} \end{matrix}$$

Web material thickness

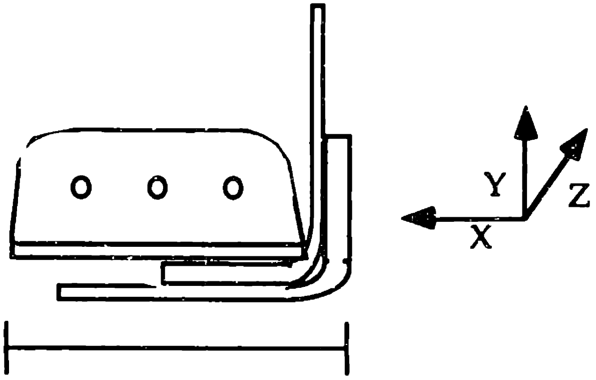


$$D \begin{matrix} Z^{3}_{1/1} \\ Z^{3}_{2/1} \end{matrix}$$

The nomenclature used to describe these dimensions is discussed in Appendix II.

Descriptive Equation for X-Direction Dimension

Next, a model is derived that describes the critical dimension on the assembly in terms of dimensions for the component parts and the locations established by the tool index points. Below is a simplified equation used for the purposes of this example.



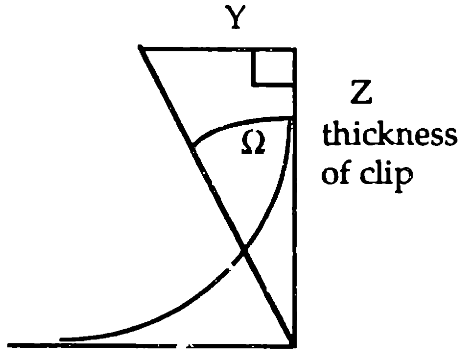
$$\underset{\Delta}{\text{Gap (+) or Interference (-)}} = \text{Displacement with Tool Index*} - \text{Length of clip} - \text{Thickness of angle} - \text{Thickness of web} - \text{Impact of angle angle} - \text{Clip Chamfer intersection}$$

* Assumed to be constant = 3.1333 per tooling drawing.

Or using the proposed nomenclature in Appendix II:

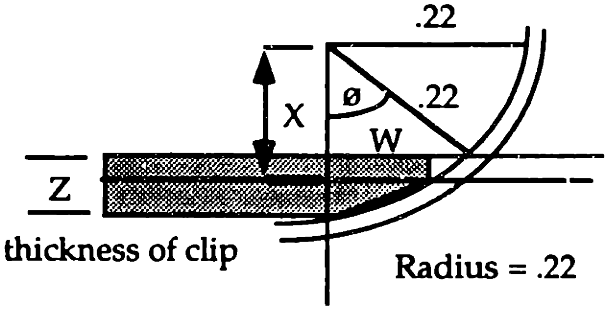
$$\Delta = 3.13333 - D \genfrac{}{}{0pt}{}{Z^{1}_{1/1}}{Z^{1}_{2/1}} - D \genfrac{}{}{0pt}{}{Z^{2}_{1/1}}{Z^{2}_{2/1}} - D \genfrac{}{}{0pt}{}{Z^{3}_{1/1}}{Z^{3}_{2/1}} - Y - I$$

The variables Y and I are derived based on the geometry surrounding the clip to angle interface. For instance, Y captures the impact to the analysis if the angle of the angle (component part) is not 90°. If the actual angle is some angle greater or smaller than 90°, the angle deflects the clip at the intersection point in a way which changes the total in the X direction. Below is a view of the geometry in question.



Displacement due to angle $Y = Z * \tan \Omega$

The interference point between the clip and the angle may actually be at the base of the chamfer instead of at the end of the part. This is because the radius of the angle begins to rise above the horizontal position before the end of the clip can mate to the angle, thus deflecting the clip a bit. An estimate of the distance to radius/clip intersection can be calculated using the following set of equations:



$X = .22 - Z + .02$ (pad on clip)

$ø = 90 - \text{ASin}(X/.22)$

$W = .22 * \text{Sin } ø$

Approximate clip intersection point $I = .22 - W$

A few sources of potential variation were assumed to be insignificant for this analysis. For instance, the tool index point was assumed to be fixed in the assembly tool. Depending on the repeatability of the tooling concept, this may not be a good assumption. However, in this case the clip was quite easy to locate using the index point, so the assumption seems valid. Another source that was ignored was the impact of the web angle. It was felt that since the tool clamped the web and angle in the correct position relative to each other, the impact from the angle was minimized.

Predicting Stochastic Processes

In order to adequately predict the outcome of stochastic processes, three primary pieces of data are needed:

1) Distribution;
2) Estimate of central tendency; and
3) Estimate of the spread of the distribution.

The more accurate the estimates describing the processes, the more accurate the final analysis of the assembly.

There are three principle ways to obtain the information necessary for this analysis:

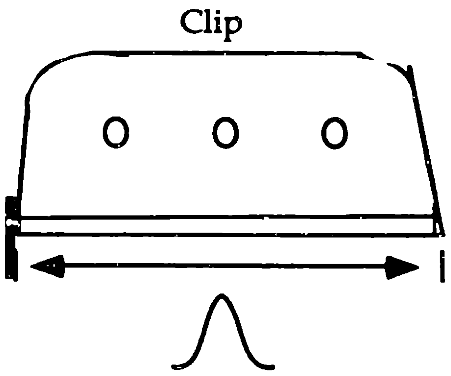
1) Obtain actual data regarding the process selected for part production. This would include process capability information and distribution with a general assumption being that future parts will have similar characteristics.
2) Use your best guess as to the type of distribution. Often a normal distribution is an appropriate guess for certain types of processes. Others would be better characterized using another type of

distribution. Assuming a process capability of 1.0 is a an adequate guess for this analysis.

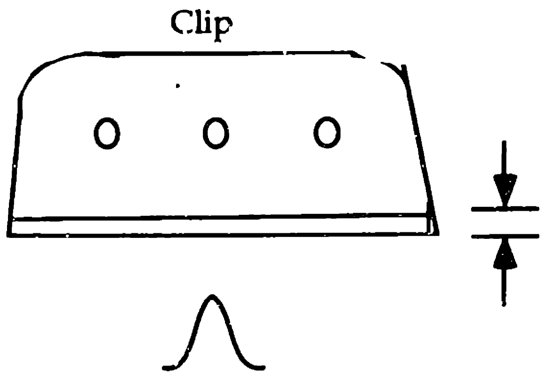
3) A tolerance band established as part of the design can be used in place of a process distribution (uniform with mean equal to the nominal value).

This approach may not seem very accurate. However, for the purposes of the simulation it will be accurate enough. If there is concern about the assumptions used for the analysis, the distribution selected and the descriptive statistics used can be considered a variable themselves and changed for each run of the simulation to determine the impact of the initial assumption.

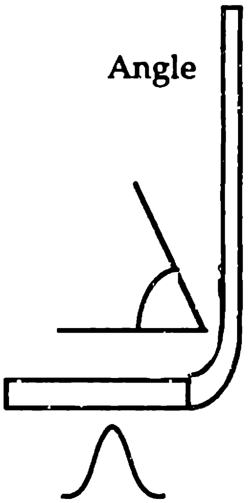
For the sill assembly example, process data were obtained by measuring existing component parts to determine process characteristics. Below is a quick summary of what was found during data collection. Appendix III contains more detailed results of this measurement study.



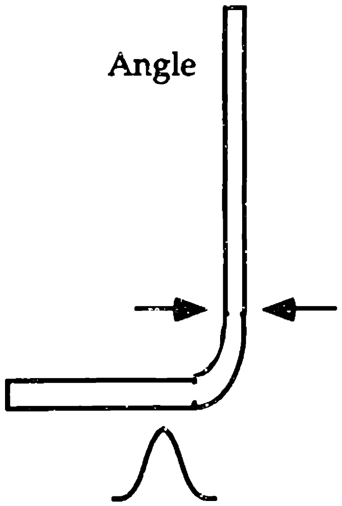
Clip length is distributed
Normal (2.9312, .0009)



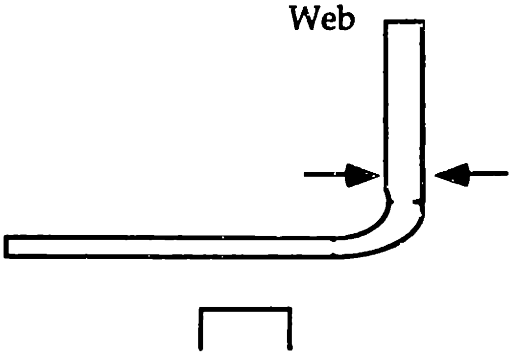
Clipthickness is distributed
Normal (.0826, .0039)



Angle of angle is distributed
Normal (89.63°, .63°)



Angle thickness is distributed
Normal (.1028, .0015)



Web thickness is assumed
Uniform(.056, .010)

Assembly Simulation

Simulation of the assembly is the next step. Each iteration involves the random (Monte Carlo) selection of a value for each of the variables being investigated, based on the assumed underlying distribution. The result of the dimension links are analyzed and the position of the point of interest is determined. The equation derived above identifies whether there will be a gap or an interference between the clip and angle when the parts are indexed per the tool.

One iteration for the simulation run in the sill assembly case is shown below:

Iteration # 1 for Sill Assembly Simulation

Randomly generated

Clip length = 2.9297
Angle thickness = 0.1038
Angle angle = 90°
Clip thickness = 0.0870
Web thickness = 0.0648

Calculated Values

Radius intersection = 0.0620
TAN of angle = 0.00

$\Delta = -.0269$ Interference

Results of the Simulation

The results based on 100 iterations are shown in Figure 5.9. The analysis shows that there is indeed a problem with the current tooling concept. It turns out that in this case that variation in the process is not a major issue; a rare situation. A basic assumption in the analysis is that the underlying distribution for the build-up in the X direction is itself gaussian.

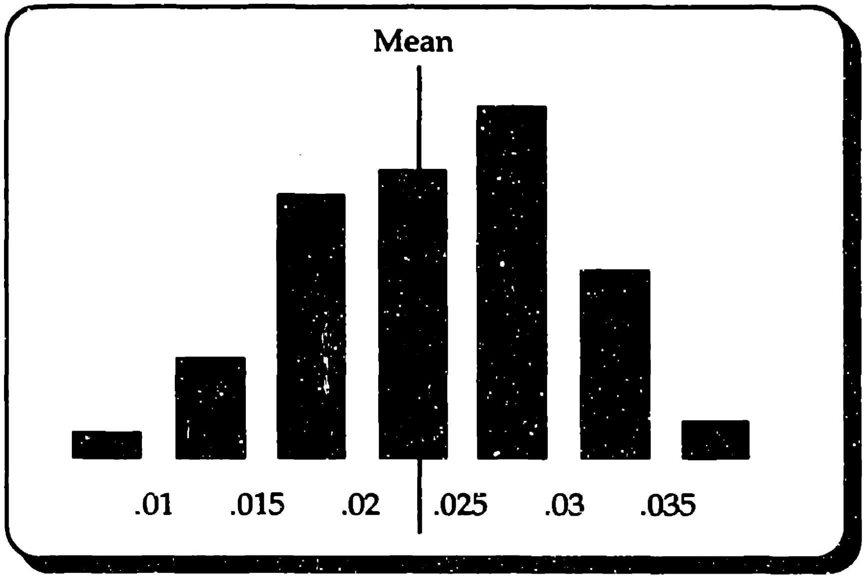
As a check, the simulation was run again with the new location of the tool index point for the clip. The results, as shown in Figure 5.10, are promising. It shows an assembly process which is within control and capable of meeting the requirements set out by the design engineers.

Based on a series of relatively simple steps, and the use of a CAD-based development tool, the engineer can determine that the process as designed will not work. What's more, a change to the tool index concept could be accomplished and evaluated within a few minutes. This is the power of forcing the integration of product and process early in the life of a program. The power is in the continuing PDCA cycle where "check" becomes a part of each incremental step in the definition of product and process designs.

Figure 5.9

Results of Simulation Shows the Problem With Current Design and Tooling Concept

Distribution of Interference Between Clip and Angle Based on Original Design/Tooling



Greatest source of variation

Angle of angle

Process Statistics

Process Mean	0.0233
Process Std Dev	0.0066
Range	0.0047

Cost of Quality

Predicted Rework	100%
Predicted Scrap	0.0%
Total Quality Cost	$ 50 / AP

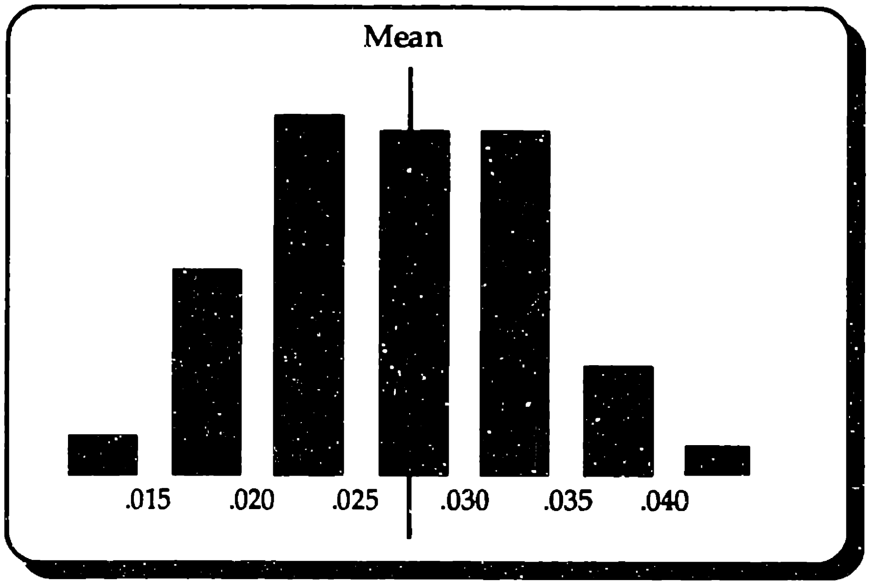
Assembly Process Capability

Cp	0.0
Cpk	0.0

Figure 5.10

Results of Simulation With Change in Tooling Index

Distribution of Gap Between Clip and Angle With New Tool



Greatest source of variation

Angle of angle

Process Statistics

Process Mean	0.0267
Process Std Dev	0.0066
Range	0.0047

Cost of Quality

Predicted Rework	0.0%
Predicted Scrap	0.0%
Total Quality Cost	$0/AP

Assembly Process Capability

Cp	> 1.0
Cpk	> 1.0

5.5 Potential Computing Solutions

Several of the building blocks necessary to develop these new software tools are currently available or in the later stages of development. For instance, software tools which perform process simulation analysis are currently available. One package, Variation Simulation Analysis (VSA) provides a CATIA™ based tool for assemblies of up to 100 components[2]. It uses the conventions of Geometric Dimensioning and Tolerancing (GD&T) to study the impacts of variations in surfaces. Within the method is the ability to study the impact of assembly sequence differences. The sequence is necessary for the analysis to take place. One drawback in the software package is the fact that no method exists to easily establish the assembly sequence. In addition, no animation capability exists.

Another building block, graphic visualization software, has been used in recent years to provide excellent visual representations of complex designs. The same technology can certainly be used in the context of assembly animation. It can also be used to help produce a graphic-based tool for establishing the assembly sequence.

Specific computing needs for each of the software tools include:

- **Establish mating links for assemblies**

  The system will need to track a series of local index point coordinate systems in the form of vectors for each point of a mating component, or for several on a surface of a component. A description of component links would also be stored within the computer.

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[2] VSA is currently being combined with another geometric analysis package called Valisys for use on CATIA™.

- **Tooling Index Scheme**

  The tool index icon will be treated just as a component part within the system. However, a special identifier will establish it as a tool, ensuring accuracy of component parts lists, etc.

- **Precedence Network**

  Establishing a precedence network based on the selections of the engineer is the primary action of the system. The graphic manipulation will also be important. The components should move into place in a real-time fashion after their selection.

- **Assembly Animation**

  Graphic visualization systems have allowed the real-time manipulation of 3D solids on the screen by "stripping off" unnecessary information associated with the geometry. This kind of system would be appropriate for this assembly animation software tool.

6. Summary of Findings and Recommendations

6.1 Major Findings

Analysis of the concurrent development process used in Boeing's 777 program indicates several areas of potential improvement. Major findings from this project include:

- Concurrency of product and process design is not sufficient to meet the goals of the project; to quickly develop high quality new products to the market in a cost effective manner. Effective integration at each step in the design process is the key to the success of new products.
- In order to improve the degree of integration in product and process design, the development team must focus on interface information transferred between engineering groups. This information (i.e. critical dimensions, part locations, functionality etc.) is the backbone of an integrated development effort.
- A "pull" system model is appropriate for the transfer of information between engineering groups. Rather than providing large packages of completed (or as complete as possible based on the schedule) engineering drawings, small bits of information transferred based on a pull schedule would improve the overall performance of the development process.
- In order to effectively integrate product and process design, a new set of CAD-based development tools are necessary for analysis of assembly processes. Consideration of component-to-component and component-to-tool interfaces, as well as the sequence of assembly, is important to the thorough analysis of assembly processes. In addition,

the variation of component parts must be considered when designing an effective assembly process.

6.2 Recommendations

Specific recommendations falling from these findings include:

- Work to develop CAD-based assembly process development tools which allow the engineer to interactively establish the sequence of assembly for a given assembly, to view the assembly in an animated form on the computer and analyze the results of the nominal assembly, and to analyze the impact of component variation on the assembly process using an assembly variation simulation tool.
- Implement an integrated schedule system based on the concept of a pull system for the transfer of interface information. The use of the design structure matrix tool by the DBTs will allow the delegation of detail scheduling task to lower levels in the organization, while maintaining rigorous program-level management control.
- A "partial design freeze" concept should be instituted to allow the stabilization of certain key attributes of the design at discrete periods of time during the development process. Changes to the frozen design would be made only within specific guidelines. The final configuration of the product design would evolve as a greater portion of the design is frozen.
- Incorporate the PICA cycle concept into the 777 Concurrent Product Definition process in order to ensure integration at each step in the design, not just at the scheduled design stages.

6.3 Implementation

While no change is easy, many of the concepts and recommendations proposed in this thesis could be implemented relatively painlessly on the next airplane development projects. Factors which will help the implementation include the fact that there is now a large population of CATIA-literate engineers who could move to the next stages of process analysis using CAD. Also, the basic building blocks for the development of the software tools proposed earlier are already available. The development of the tools will require the integration and packaging of these relatively new technologies.

6.4 Areas for on-going research

There are many areas of potential research related to this new look at concurrent development including:

- Organization structures which enable the integration of product and process should be explored. Specifically, the concept of separate teams at various stages of the design process is an interesting area.
- Concepts of configuration management with regards to the partial design freeze concept and the potential implementation on CAD databases.
- Deployment of requirements for the design of a complex products. Also, how to accommodate in these requirements issues such as program vision, customer participation, use of quality function deployment or other structured methods.

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Appendix I

History of Boeing Tooling Philosophy

Tooling Philosophy at Boeing

Evolution of Assembly Techniques

America's roots in mass production can be traced to the mid-1800s when several fire arms makers began to product guns with "uniform" parts. This significant step, later described as the introduction of interchangeable components, required the use of new manufacturing techniques in order to obtain the interchangeable parts. The introduction of precision machining equipment were key to the effort to improve uniformity. As the concept of interchangeable parts became popular, the techniques of mass production transferred to other growing industries such as bicycles, typewriters, and automobiles.[1]

Assembly techniques and design concepts used for airplanes have undergone a similar transformation the years, but are now changing at an ever quickening pace. Modeled after the techniques used in the auto industry, tooling concepts used for the mass production of airplanes were introduced at Boeing during World War II. At the time, the company was faced with an incredible production challenge; producing one B-17 every 49 minutes.

Tooling for assembly of an airplane has long played a critical role in the production process. The complexity of the airplane, the size of assemblies, and the shear volume of component parts to locate for assembly makes the job of assembly tooling difficult.

Another complication is the design philosophy employed by Boeing to ensure the fail-safe nature of the airplane's structure. A design philosophy is employed which provides many "load paths" for the structure to avoid

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[1] Smith, M. Roe, Class notes - Government and Technology, Massachusetts Institute of Technology, April 26, 1993.

catastrophic failure of the structure. This concept is effected by using many more assemblies of smaller sheet-metal components, versus larger, integral parts. Assembly tooling must locate all these parts, plus ensure proper alignment for subassembly installation later in the production process.

Finally, the nature of the contours on an airplane (based on the optimum aerodynamic surfaces) make the production portions of the airplane very difficult. For instance, by design body panels often have extra creases or other "complex contours" which are very hard to document in engineering drawings, let alone fabricate. Yet, contours added to a body panel must match all interfacing subassemblies or other body panels.

The most important element of a process design for assembly is the tooling philosophy to be incorporated. Since the advent of the jet aircraft, Boeing's production methods for assembly have undergone many incremental transformations. However, for the purposes of this Appendix, I will discuss three "eras" of past and current Boeing tooling philosophy, plus the next potential era of tooling. The eras include:

- Era I Early Airplanes
- Era II Middle Generation
- Era III Newest Generation
- Era IV Next Generation

Below is a brief description of each of the "Eras" of Boeing tooling philosophy.

Era I Early Airplanes

Boeing was the first in the industry to produce a successful jet airplane, the Model 707, using a tooling philosophy with roots in the bomber production days of the WW2. Techniques used for the assembly of this aircraft were used by Boeing for almost forty years.

Figure A1.1 depicts the process involved in the transition of the engineering product definition into a finished body panel assembly. The procedures of production used to ensure that the contours as designed become part of the product, are the realization of the tooling philosophy prevalent in the company. Each step in the transfer process for this era is described in more detail below.

1) The contour of the airplane is defined by engineers, based on aerodynamic analysis, and recorded in an engineering drawing in a form called "loft lines".[2] These lines provide shape information for each segment of the airplane. A line is drawn for every few inches of the airplane body or other structure. Contours between the loft lines are considered to be smooth transitional curves.

2) Transferring the contours described by the loft lines is the next step. Templates (master tooling templates or) are fabricated from the contour lines by skilled machinists. In turn, MTTs placed together can form what is essentially a slice of the body. The contour for a specific slice of the airplane is now physically defined.

3) Next MTTs are used to fabricate what are called headers. Placing the headers in precise locations only a few inches apart provides the skeleton for a solid model for the outside contour of the airplane. Once plaster or another type of "mud" is placed between the headers, a smooth approximation of the outside of the

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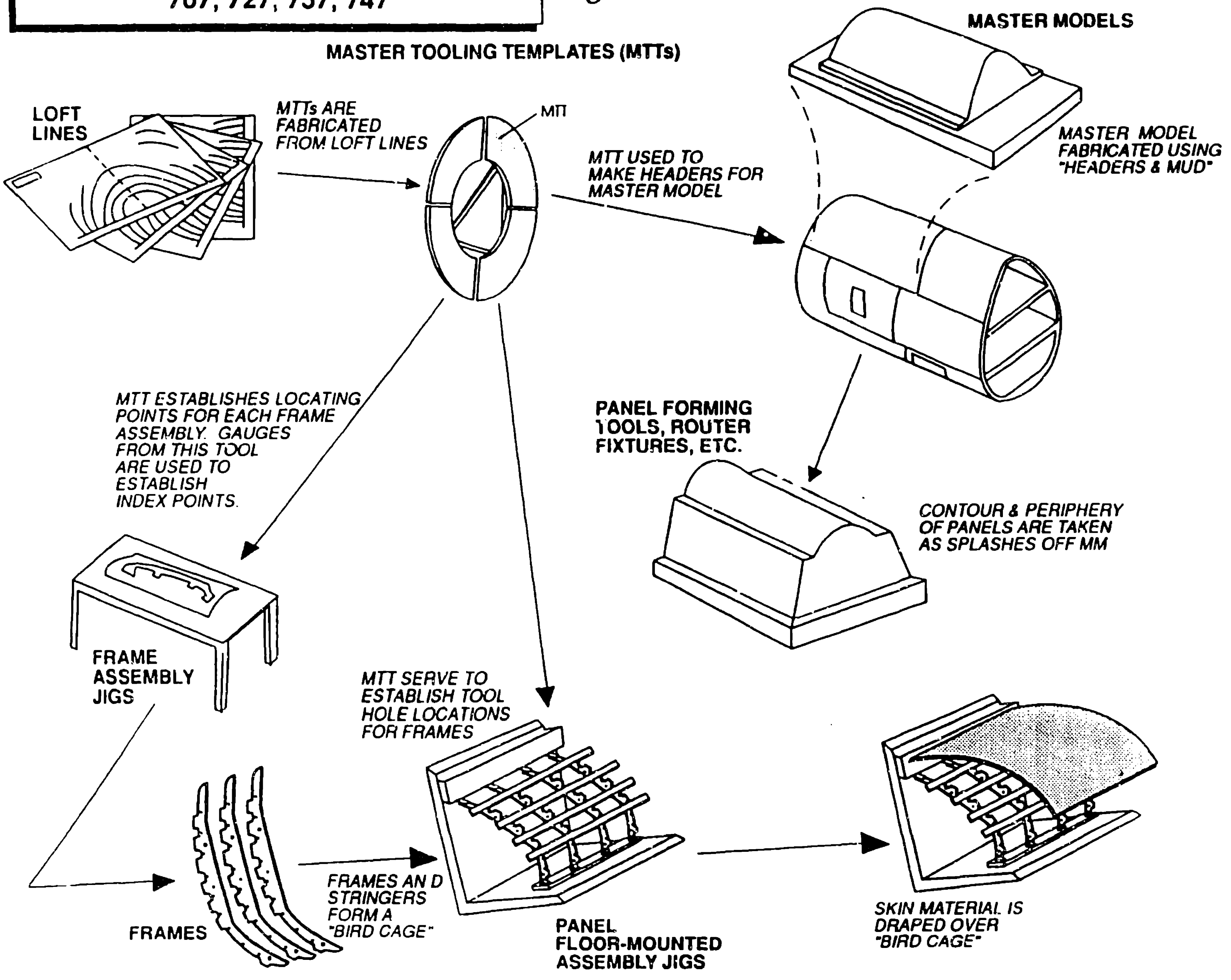
[2] Loft lines got their name from the days when engineers used to work in the "loft" of Boeing's original building. A picture of early engineers working at long tables, holding huge sheets of paper can be seen in the Museum of Flight in Seattle.

EARLY AIRPLANES, 1940 - 1970
707, 727, 737, 747

Figure A1.1



airplane is obtained. This model, described as a master model, becomes the ultimate authority for the airplane contour. From this model, fabrication tools such as forming tools for body skin panels and router fixtures are produced. A plaster "splash" is used to transfer the shape from the master model to the tools being fabricated.

4) MTTs are also used to provide location points for assembly tools. This includes the tools used to build the body frame sub-assemblies and the final panel assembly jigs. Positioning in these assembly tools is dependent on the MTT. Gauges based on the MTTs are used to establish and to maintain the assembly tools.

5) The final contour of the body is established as the skin material is "draped" over the framework of frames and stringers. Assembly tools which locate these component parts and the shape and contour of the skin panels prior to being draped ultimately determine the final contour of the cross-section.

Era II Middle Generation

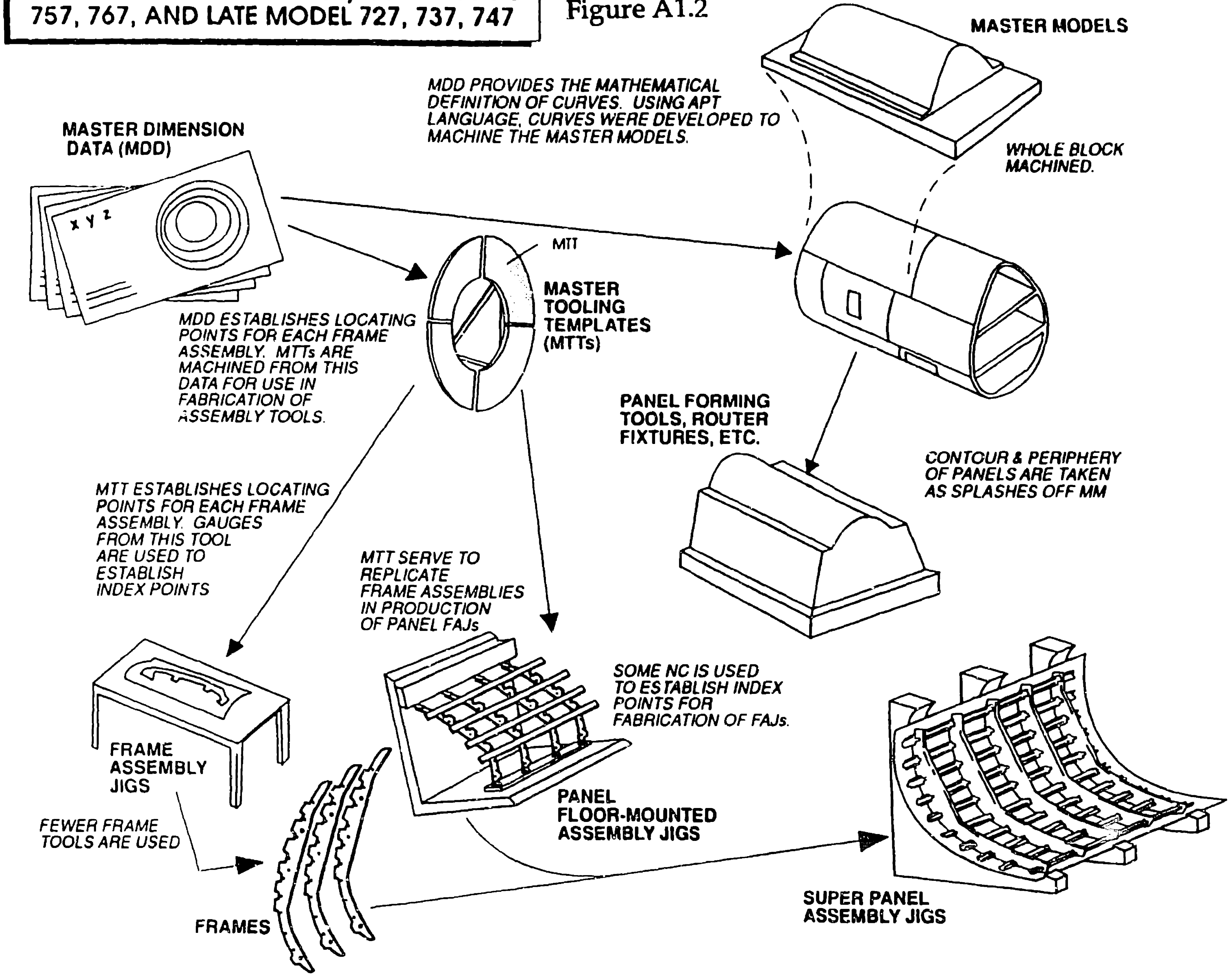
The second major advancement in Boeing's tooling philosophy came about with the design and production of late models of the Models 727, 737, and 747, plus the new Models 757 and 767 during the 1970s and 1980s. While radical design changes did not occur, the use of digital data to define the configuration of the product began to find its way to the production floor.

Figure A1.2 depicts the tooling philosophy as it stood during this period. The major changes in this new era of tooling were:

1) The manual drawn loft lines are replaced by data points defined by the engineering staff. While a common database still do not exist, the digital data is recreated using APT programming language, then used for machining the master models from whole blocks.

MIDDLE GENERATION, 1970-1990
757, 767, AND LATE MODEL 727, 737, 747

Figure A1.2



2) MTTs are also used for use in the production of panel and frame assembly jigs, as well as to fabricate gauges for tool maintenance.

3) Digital data are used to establish index points for the assembly jigs.

4) A new assembly step is used that brings together a larger section of the frame/stringer "bird cage" for production of a "super panel".

Many advantages existed in these early steps toward the use of digital data in the tooling philosophy. First, the use of data rather than relying on the transfer of data from lines to fabrication machines reduced the possibility of error. Second, two physical transfers in the building of the master model headers are eliminated. Finally, fewer gauge developed index points for the assembly jigs reduces the possible for the inclusion of even more variation.

Some things did not change. The airplanes of this era continued to be defined by tool, not by the drawing itself. The existence of a master model ensured that the final authority regarding the shape of the product rested with the tooling.

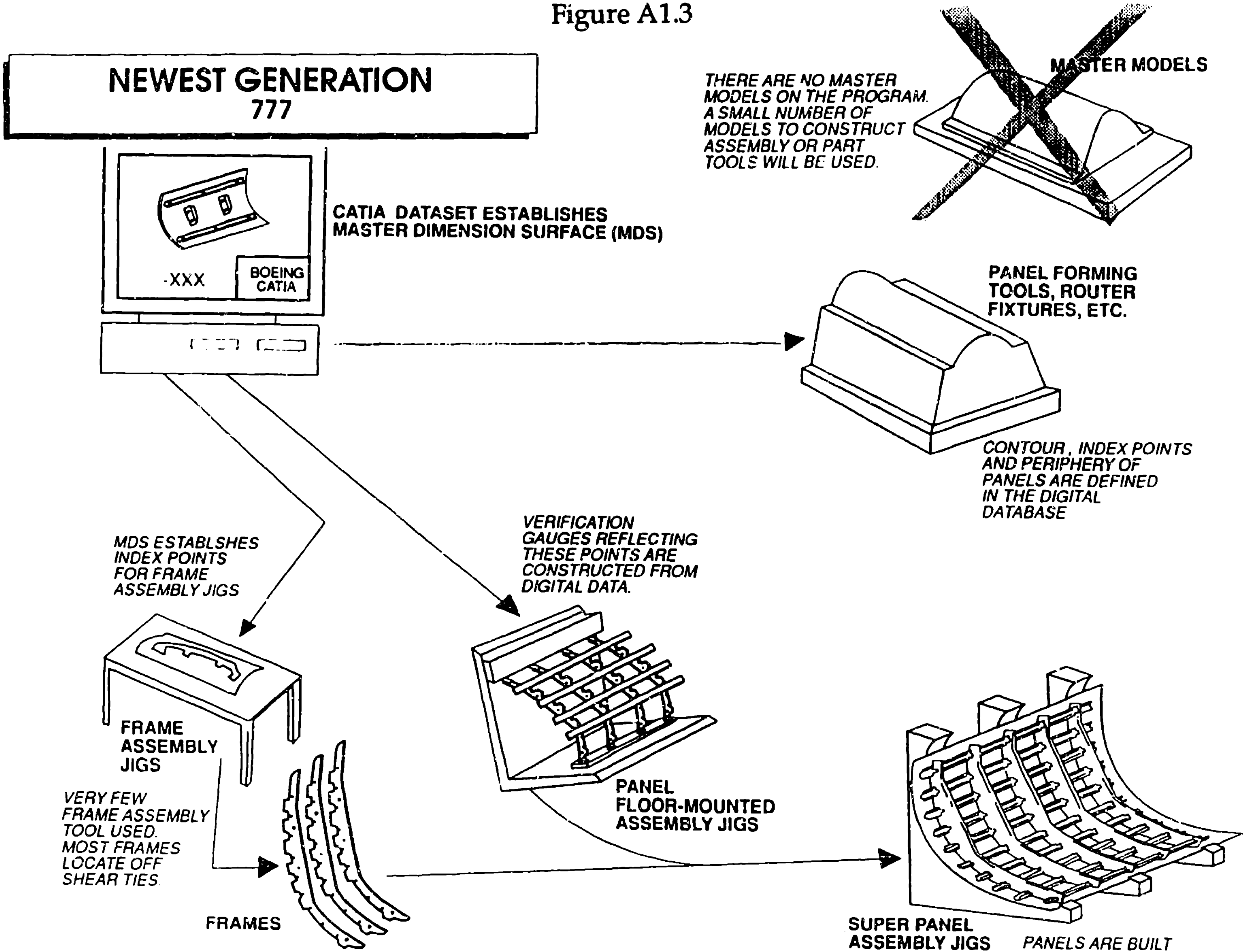
Era III Newest Generation

With the production of the Model 777, Boeing has made it greatest advancement yet in the evolution of tool design. For the first time, Boeing designed the entire plane using computer-aided design. The digital definition of the airplane could, in turn, be used to define the shapes used for the product.

Figure A1.3 depicts the tooling philosophy used for the development of the Model 777. The major changes in this era of tooling are:

1) The design of the plane is entirely contained within the CATIA™ system. Points used to define the surfaces are extracted and inspected to ensure that there are no irregularities.

Figure A1.3


NEWEST GENERATION
777
-XXX
BOEING CATIA
CATIA DATASET ESTABLISHES MASTER DIMENSION SURFACE (MDS)
THERE ARE NO MASTER MODELS ON THE PROGRAM. A SMALL NUMBER OF MODELS TO CONSTRUCT ASSEMBLY OR PART TOOLS WILL BE USED.
MASTER MODELS
PANEL FORMING TOOLS, ROUTER FIXTURES, ETC.
CONTOUR, INDEX POINTS AND PERIPHERY OF PANELS ARE DEFINED IN THE DIGITAL DATABASE
MDS ESTABLSHES INDEX POINTS FOR FRAME ASSEMBLY JIGS
VERIFICATION GAUGES REFLECTING THESE POINTS ARE CONSTRUCTED FROM DIGITAL DATA.
FRAME ASSEMBLY JIGS
VERY FEW FRAME ASSEMBLY TOOL USED. MOST FRAMES LOCATE OFF SHEAR TIES.
FRAMES
PANEL FLOOR-MOUNTED ASSEMBLY JIGS
SUPER PANEL ASSEMBLY JIGS
PANELS ARE BUILT IN EVEN LARGER SIZES

2) The contour data is then used to fabricated panel fabrication tools, frame assembly tools, and panel assembly jigs. Gauges built from digital data are used to verify index points on assembly jigs.

3) With this advancement, the final configuration authority for the shape of the airplane rests with the engineering design. There are no master models for the 777, only a few models used for tool fabrication purposes.

4) Many tools are equipped with measurement capabilities so that key characteristics in the assembly can be controlled. "Gaugeless tooling" has provided an opportunity to move toward data-driven production.

At the time of this writing, production of the 777 had begun with no major problems. This final evolution in assembly tool-driven production seems to be a success. It is believed by many at Boeing that the next evolution in airplane production will eliminate the use of most major assembly jigs.

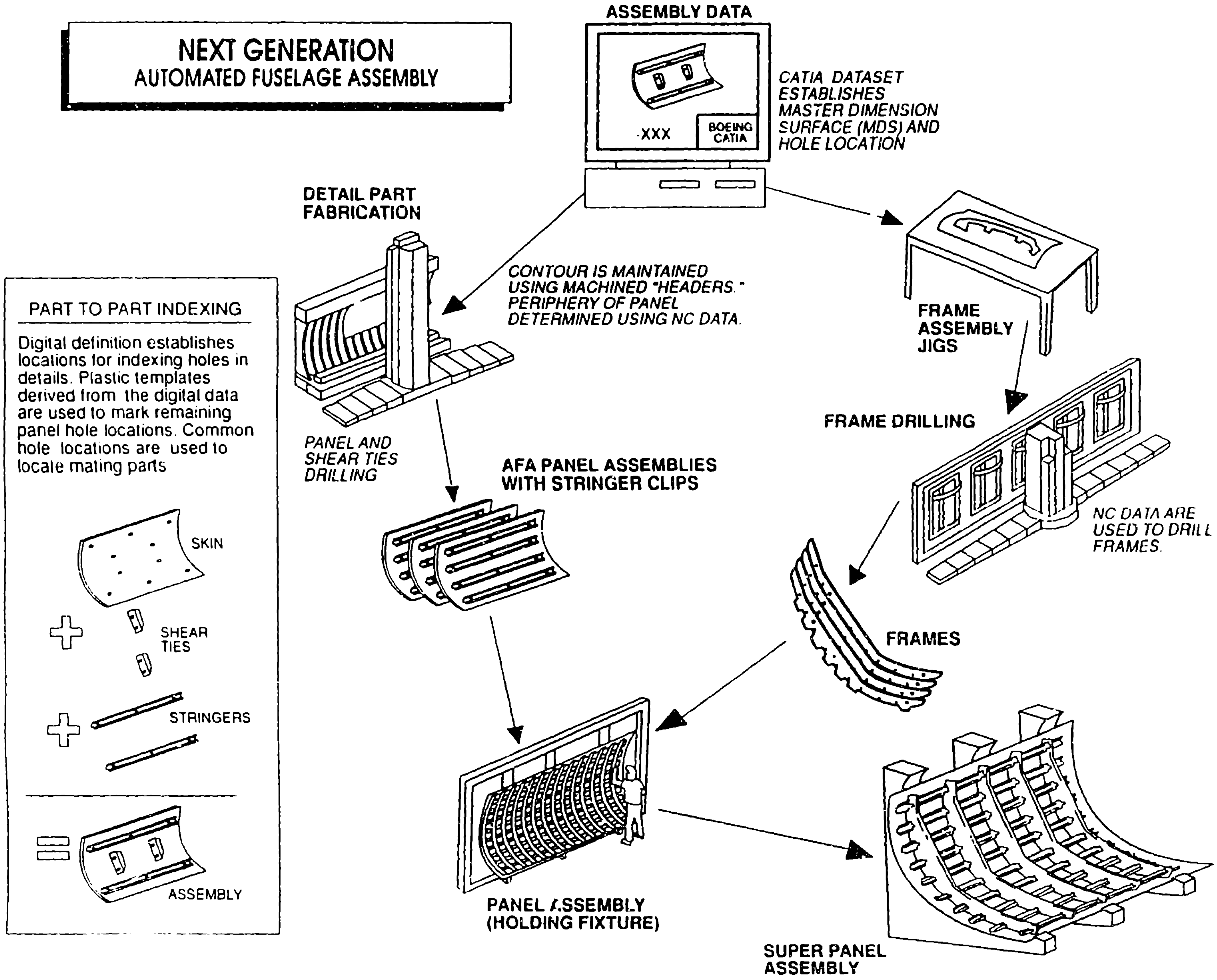
Era IV Next Generation

A proposal is currently being tested at Boeing that would utilize digital data to index component parts relative to each other, rather than using a tool to physically locate each part. The Automated Fuselage Assembly (AFA) concept is based on machine tool and automated riveting technology. Figure A1.4 depicts this new tooling concept. The major changes include:

1) Components are located relative to each other, and to the digital design, thus eliminating the need for assembly jigs for locating.

2) Numerically controlled equipment are used to drill precise holes in the components and relate mating parts based on global reference points.

Figure A1.4



Digital definition establishes locations for indexing holes in details. Plastic templates derived from the digital data are used to mark remaining panel hole locations. Common hole locations are used to locate mating parts

It has not been determined how far the AFA concept will be employed across Boeing. However, it has shown to have many benefits in its initial trials because of its improved quality and increase in productivity.

Impact of tooling philosophy

Choice of a tooling concept has many implications for the development of an airplane. In the end, the philosophy will impact the investment needed to produce the product, the ability of the organization to obtain assembly process data, the flexibility of the production line, and the final quality of the products produced.

Even though Boeing has evolved beyond its early tooling philosophies, there is still a master model/gauge mindset within the company that may handicap the engineers designing future processes. But, just as with the movement toward interchangeable parts, the new gaugeless tooling philosophy will eventually become the standard. Very possibly, the use of NC equipment rather than assembly tooling will be a vital part of the tooling philosophy employed on the next major airplane project.

Appendix II

Indexed Pre-assembly with Assembly Variation (IPAV) Concept

Index Pre-assembly with Assembly Variation (IPAV)

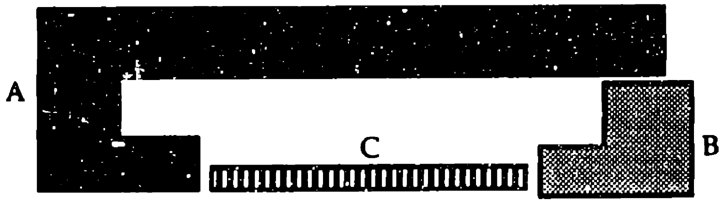
In his thesis of 1992, Dari Shalon presented a framework (what he called IPAV) for keeping track of the location of interfacing surfaces on component parts while considering the impacts of tooling concepts, assembly sequence, and process variation in the dimensions of component parts. Below is a further dicussion of the IPAV concept, with a few refinements, using a simple assembly to demonstrate the methodology.

Nominal Assembly

For this example, let us
look at a simple assembly
with this nominal design

Exploded View

An exploded view shows
three component parts
A - Connector
B - Connector
C - Tube

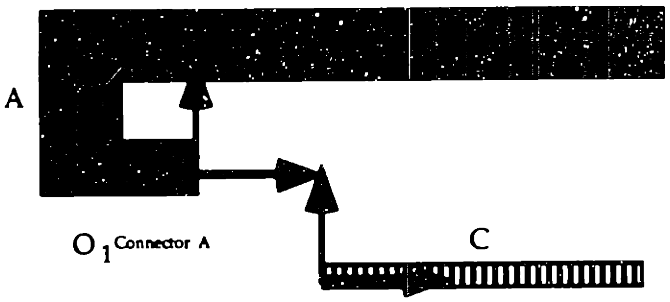


Local Index Point Coordinate System

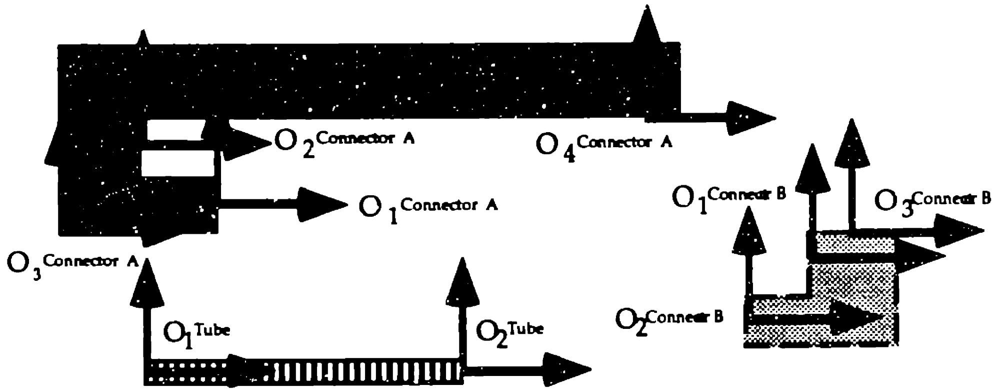
The first step in the methodology is to establish what will be referred to as local index point coordinate systems on each of the interfacing surfaces within the assembly. Interfacing surfaces are those component surfaces which must mate to other components or to the assembly tool. For instance, Establish local index at mating points.

A local index coordinate system is established on each mating surface. The local origin is marked as

O_1 Connector A indicating, index 1 for connector A.



The process is completed for each mating surface.



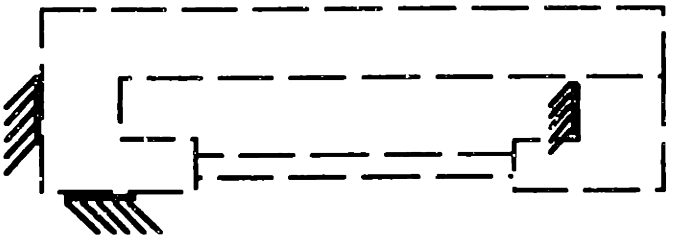
Once the component part interfaces have been established, the tooling concept must be explored. Tools will be treated as if they are components. The only difference is that they do not follow the subassemblied to the next stage in the airplane process. Therefore, mating features on the tool and on component parts must be considered and tracked.

First, the tool index concept used for the assembly is marked using index surface icons to indicate which surfaces will mate with components.

These features become the key to the final configuration of the assembly.

Tool Index Plan

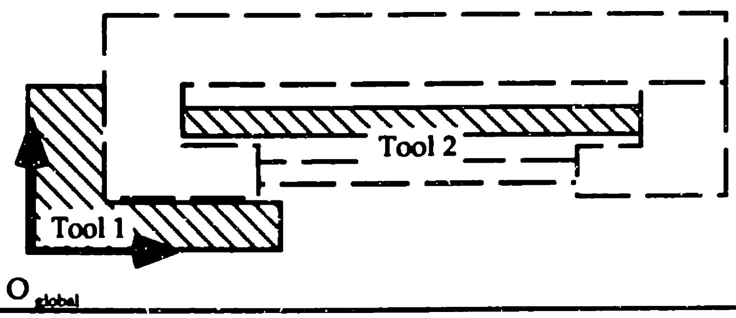
A tool index plan identifies the surfaces which are being used to locate the component parts.



Next, an assembly tool can be designed to accomplish the intention of the index plan. This tool locates the conponent parts relative to each other, the index surfaces, and to some global coordinate system. For our simple example, here is a possible tool design.

An assembly tool is designed to hold the component parts at the specified index locations. A global coordinate system is established with a known relation to the airplane coordinate system

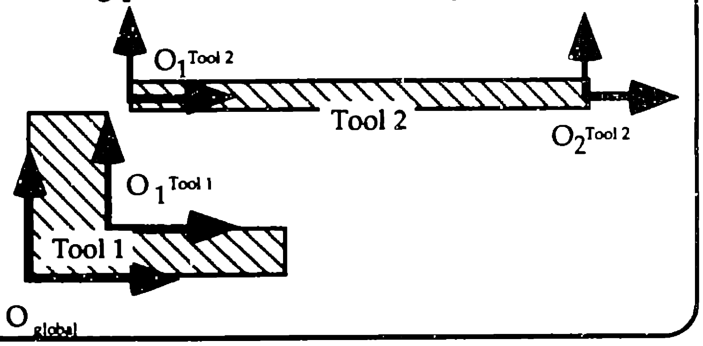
Tool Design



Interfacing points on the tool itself and the component parts must be treated in the same way that components alone were treated. Therefore, local index point coordinate systems are established for each of the mating surfaces on the tool.

Establish local index at mating points. on the assembly tool.

Each index surface on the tool will be marked with a local index point coordinate system. The same notation applies.



Local indices have now been established on the mating surfaces of both component parts and tools. It is now time to evaluate what happens as we "assemble" our sample.

Dimension Chains

Using the local indices, the location of any surface relative to the global coordinate system is the sum of the distance of translation between each of a succession of mating parts and tools from the global index point. This stack-up of dimensions will be referred to as the dimension chain.[1] Each local index coordinate system on mating surfaces are said to be linked dimensionally. That is, the coordinate systems are superimposed if they are meant to be mating parts. After our analysis, we may find that linked dimensions are not superimposed, and thus in a condition of interference or gapping.

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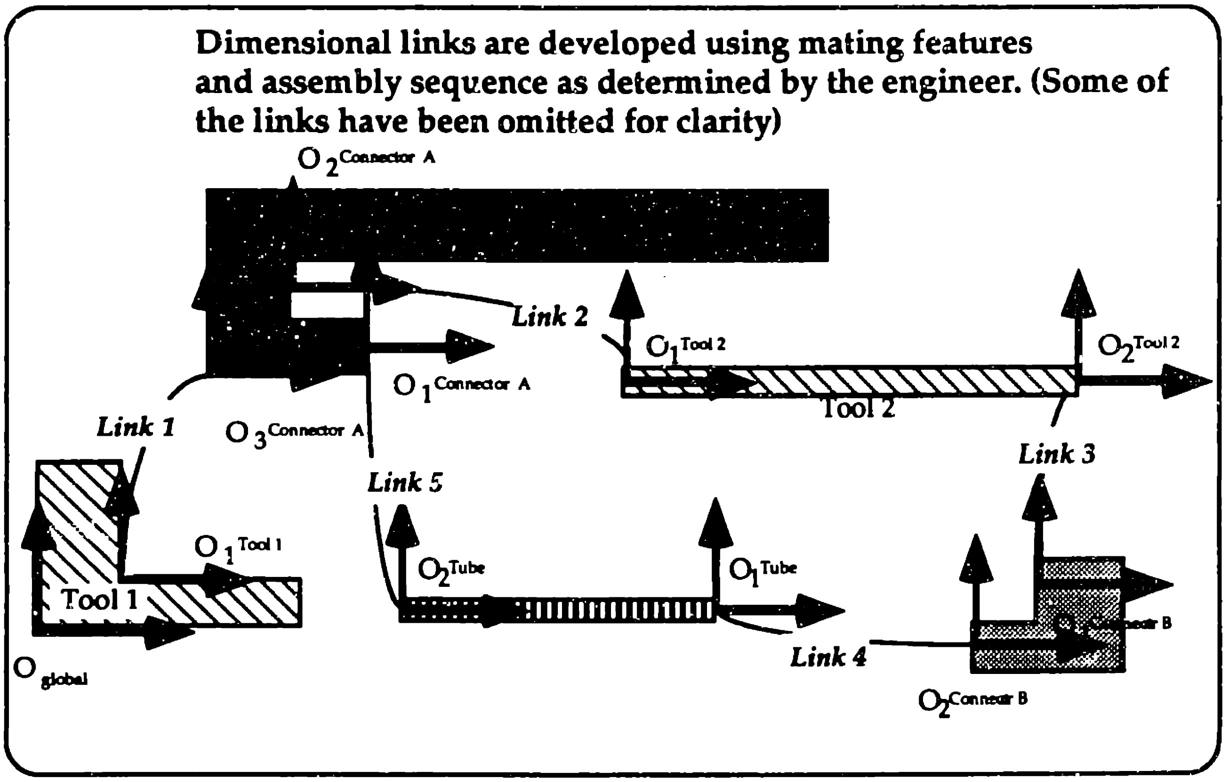
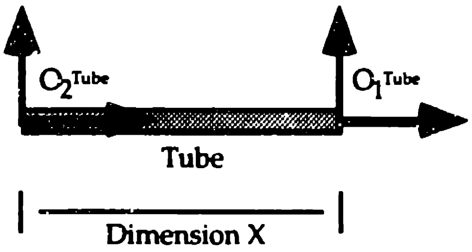
[1] Bjørke, Øyvind, *Computer-Aided Tolerancing*, Second Edition, ASME Press,New York, 1989.

The figure below depicts stylistically the "linking " of the local indices in the dimension chain.



Dimensional links are developed using mating features and assembly sequence as determined by the engineer. (Some of the links have been omitted for clarity)

Analysis of the dimension chains soon reveals that the sequence of assembly is important to the outcome. For instance, what would be the impact on the location of the connector B (relative to the global coordinate system) if the length of the tube was variable?



$O_1^{Tool\ 2}$ + Dimension X = $O_2^{Tool\ 2}$

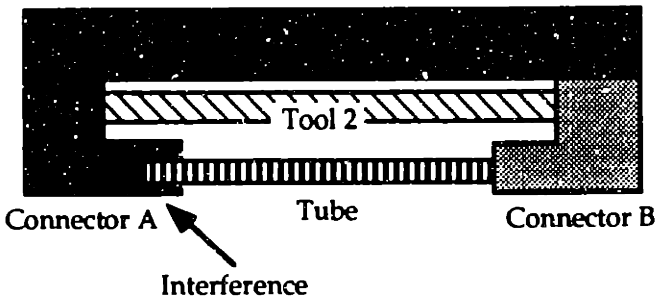
Where

X is Normal (mean, std deviation)

The impact would depend on what sequence was used for assembly.

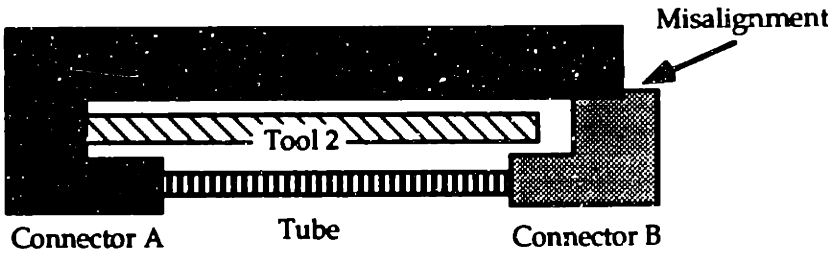
If the connector B were located using the "tool 2" before being attached to the tube, an interference between the tube and the connector A would result. The connector B would be flush to the right side of connector A.

Case 1

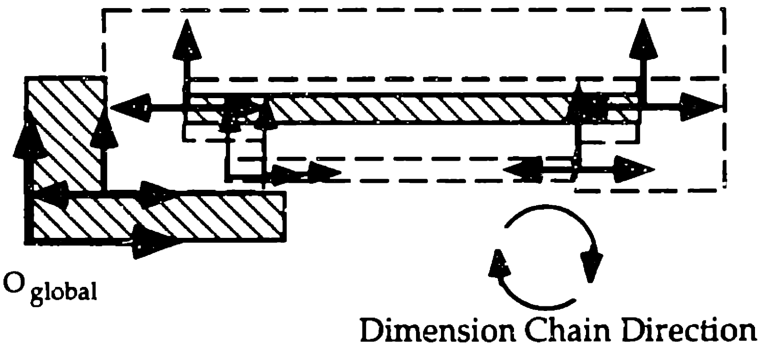


If the tube were located against the connector B first, then the two were placed as a subassembly located against connector A, the resulting assembly will look much different.

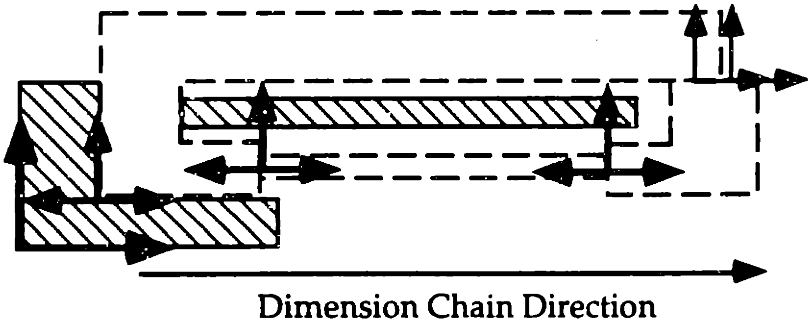
Case 2



The dimension chain can be used to determine the location of the local index by summation in the X direction. Thus providing the amount of interference or misalignment in the two cases. Each assembly sequence creates a different dimension chain. In case 1



In case 2, the dimension chain is more direct



Notation

A common notation is necessary to describe the impacts of links and dimension chains.

The amount of the interference in the X direction would be

$$\text{X component of } O_2^{tube} = X_{O_2}^{tool} + X_{O_2}^{ConnA} + X_{O_2}^{tool2} - (X_{O_1}^{ConnB} - X_{O_2}^{ConnB}) - (X_{O_1}^{tube} - X_{O_2}^{tube})$$

$$\text{Interference in X} = X_{O_2}^{ConnA} - \text{X component of } O_2^{tube}$$

The amount of the misalignment between the connectors in the X direction would be

$$\text{X component of } O_1^{ConnB} = X_{O_2}^{tool} + X_{O_2}^{tube} + X_{O_1}^{tube}$$

$$+(X_{O_2}\text{ConnB} + X_{O_1}\text{ConnB})$$

$$\text{Misalignment in } X = X_{O_1}\text{ConnB} - X_{O_4}\text{ConnA}$$

In three dimensions, each local index can be represented by a vector quantity of the three dimensions. Further explanation of the mathematics of IPAV can be found in Shalon's thesis.[2] The simplicity of this example does not do justice to the computational requirements necessary to accomplish the matrix manipulation in the three dimensional case.

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[2] Shalon, Dari, "Indexed Pre-Assembly with Variations; A Method of Representing Variations of Parts and Tools in CATIA", MIT Leaders for Manufacturing Program, Masters Thesis, June 1992 Appendix P and O.

Appendix III

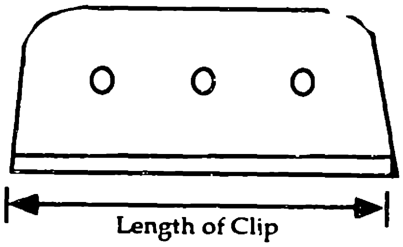
Component Process Capability Data for 757 Sill Assembly

Appendix III

Process Capability Study

Clip (-5) Length

Sample scheme: 30 parts were measured at two locations.



Nominal = 2.9333 + /- .030

Summary Statistics

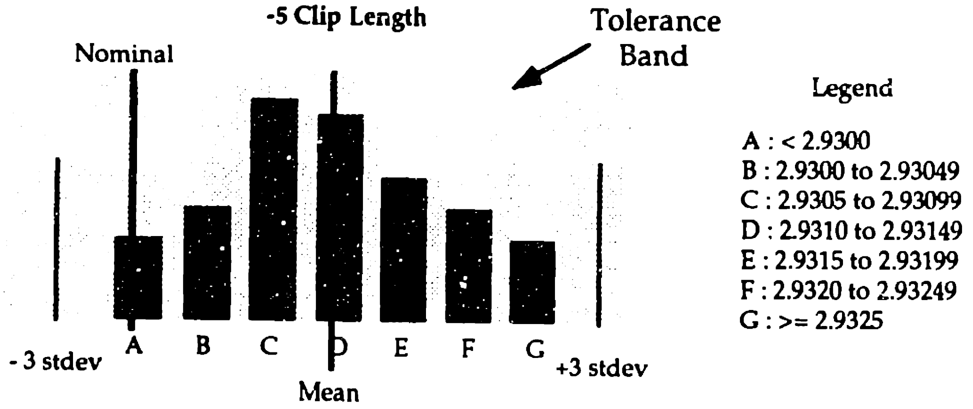
Grand mean	2.9312
Standard Dev	0.0009
Maximum	2.9331
Minimum	2.9293
Range	0.0038

No significant difference at points
No significant supplier lot differences

	Point 1	Point 2
Mean	2.9314	2.9310
Stdev	0.0009	0.0009

Process Capability

C_p	11.12
C_{pk}	10.33

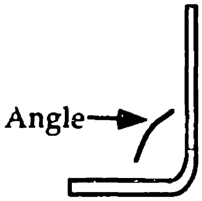


Appendix III

Process Capability Study

Angle (-7) Angle

Sample scheme: 30 parts were measured at one location for angle.



Nominal: 90 °
Tolerance: +/- 2 °

Summary Statistics

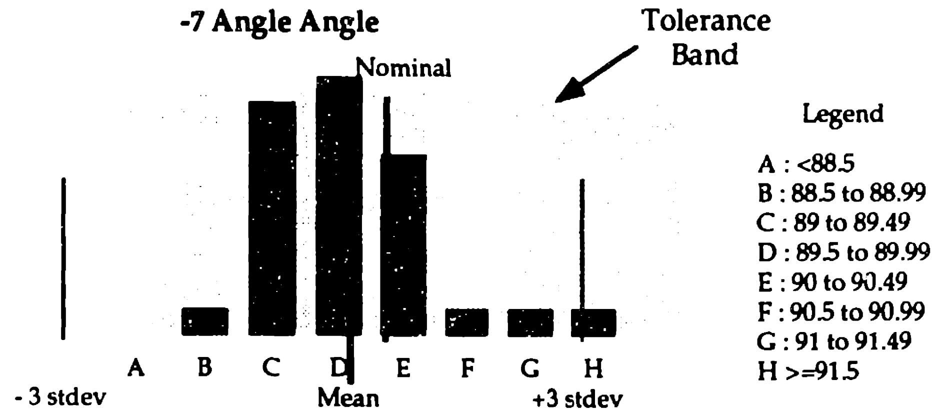
Grand mean	89.63
Standard Dev	0.63
Maximum	91.5
Minimum	88.5
Range	3.00

No significant supplier lot differences

	Mean	StDev
SP3 12/10/92	89.38	0.37
Aero 4 8/2/90	90.00	0.76

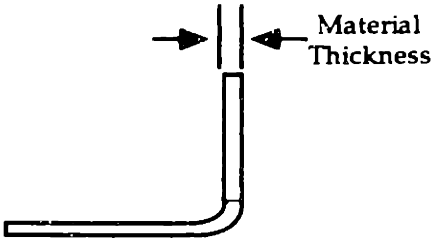
Process Capability

C_p	1.06
C_{pk}	0.86



Process Capability Study

Web (-3 and -4) Material Thickness

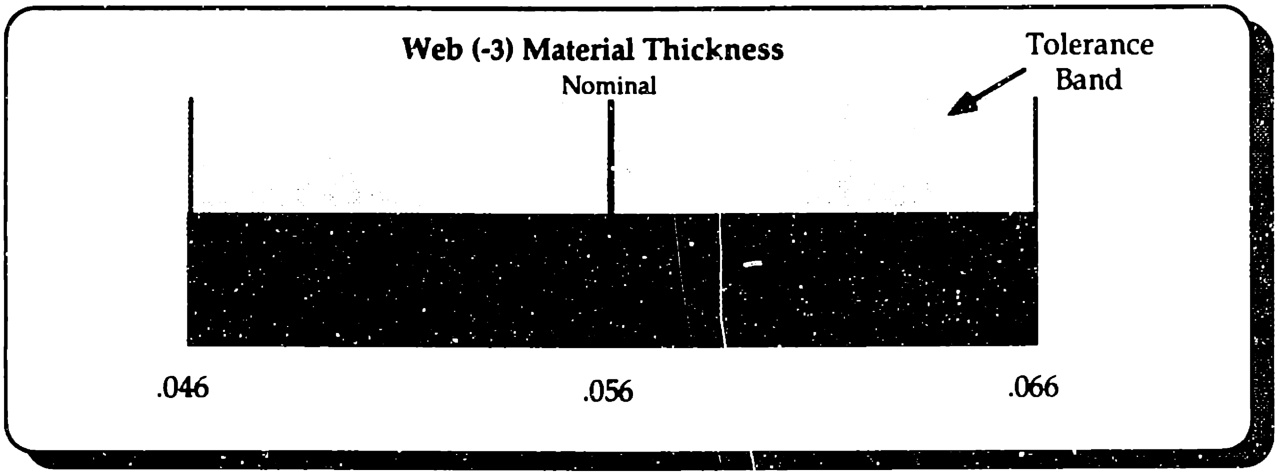


Summary Statistics

No process data available

Nominal = .056 + / - .010

Assume a uniform distribution across tolerance band.

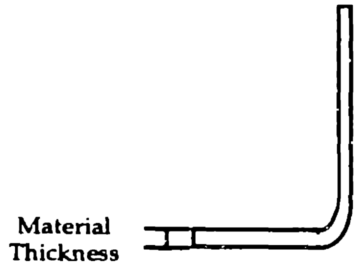


Appendix III

Process Capability Study

Angle (-7) Material Thickness

Sample scheme: 30 parts were measured at thickest portion.



Nominal = .1000 + /- .030

Summary Statistics

Grand mean	0.1028
Standard Dev	0.0015
Maximum	0.1081
Minimum	0.1009
Range	0.0072

Significant lot differences between suppliers.

	Mean	Stdev
SP3 12/10/92	.1022	.0010
Aero 4 8/2/90	.1036	.0017

Process Capability

C_p	13.63
C_{pk}	6.18