

**IMPLEMENTING PRECISION ASSEMBLY TECHNIQUES  
IN THE COMMERCIAL AIRCRAFT INDUSTRY**

by

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S.B., Aeronautics and Astronautics, MIT (1989)

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## **Abstract**

This thesis proposes a precision assembly methodology to address the significant problems created by detail part variability in the aircraft manufacturing process. Changes in the competitive environment in the commercial aircraft industry have highlighted the negative effects of variability, especially with regard to the cost and time penalties incurred through the use of custom fit, labor-intensive assembly processes. The goal of the precision assembly methodology proposed here is to simplify the assembly process by eliminating the use of assembly tooling in the production of aircraft structures.

A precision assembly methodology was developed to permit the assembly of aircraft structures without tools. This thesis describes the proposed methodology and its effect on all phases of the aircraft manufacturing process, from the initial design of the structure through fabrication and assembly. The successful application of the methodology to a typical aircraft floor structure is described in detail. Use of the proposed methodology results in reductions in product cost and manufacturing cycle times, accompanied by increases in product quality. Strategically, precision assembly will provide additional focus for existing HVC programs and drive aerospace manufacturing organizations to a position where they can become a source of sustainable competitive advantage for the firm.

While the technological implications of precision assembly will be significant, the organizational ramifications may be even more far-reaching. In fact, the advantages of precision assembly may be *unrealizable* without significant changes in organizational structures and policies. In the fabrication organization, manufacturing cells are proposed as a means of achieving precision assembly success. In the assembly organization, dedicated cross-functional teams focused on specific precision assemblies are proposed to gradually replace the existing functional organization. The successful transition of the precision assembly methodology into the factory will depend on the ability of management to lead large-scale, difficult change efforts in both the technological and social systems within the factory.

## **Thesis supervisors**

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## **Section 1. Introduction**

This thesis proposes a precision assembly methodology to address the problems created by detail part variability in the manufacturing process. The goal of the proposed methodology is to eliminate the use of tooling in the aircraft assembly process. In Section 1, a framework for the entire thesis will be provided, beginning with a statement of the problem and justification for research into new assembly processes. This section will detail the objectives of the research and provide a road map for the presentation of the arguments and ideas in this thesis. This section concludes with an overview of the research findings.

### **1.1 Statement of problem**

*The competitive environment is changing.* The competitive environment in the commercial aircraft industry has changed significantly in the last five years. The basis of competition for aerospace manufacturers has changed from one which emphasized design excellence and on-time deliveries to one stressing lower unit costs and faster delivery times. This changing focus of the airline customer is caused by a number of factors: intense and often cut-throat competition in the airline industry; the proliferation of airline CEOs who have risen through the financial as opposed to the engineering ranks; and the increasing ability of airline customers to play one aircraft manufacturer off another to obtain the best possible price.

In response to changing customer needs, aircraft manufacturers are becoming more aggressive. The Boeing Company recently lost a United Airlines order for 50 aircraft, traditionally one of its best customers, to Airbus Industrie when Airbus committed to delivering the planes faster than Boeing and at a per aircraft price estimated to be \$4 million *below cost* (Seattle Times 1993). Even McDonnell Douglas, which has lost

significant market share to Airbus in the past ten years, is making great strides in reducing the time it takes to assemble their aircraft (Aviation Week 1993).

The combination of increasingly demanding customers and increasingly aggressive competitors will force changes in the manufacturing strategy which aerospace manufacturers have historically pursued. Aerospace manufacturers must now strive for breakthrough improvements in reducing the cost of their aircraft while simultaneously making the improvements in delivery time required by their customers. In fact, two key objectives in the industry during the next five years are significant reductions in aircraft cost and production cycle time.

*Variability in manufacturing processes imposes significant cost penalties.* Variation in the nominal design, in the fabricated detail parts, in the assembly tooling, and in assembly procedures all lead to parts that do not fit on assembly. Labor-intensive, custom-fit assembly processes are required to build structures from these inconsistently variable parts. The negative impacts of these inefficient assembly processes extends far beyond the easily-tracked assembly labor costs. The hidden costs associated with excess inventory, increased cycle time, and highly variable factory process flows are significant and limit the ability of aerospace manufacturers to provide their customers with high quality, low cost products. In fact, one study documented how 40% of the labor hours required to assemble the main entry doors of a passenger aircraft was spent reworking "good" parts -- parts that were built within the specifications of the drawing.

*Existing assembly processes have institutionalized this variability.* Aerospace assembly organizations have developed an extraordinary capability of being able to build safe and reliable aerospace structures out of inconsistently variable detail parts. Their skill at accommodating variability has masked the fact that they are merely addressing the



effects of detail part variability, not the cause. The more successful they are in the construction of acceptable structures, the more they institutionalize the use of assembly tooling, leading to costly rework and waste.

## **1.2 Goal of the research project and focusing assumptions**

The goal of this research project was to study the feasibility of using precision assembly techniques as a means of providing the stimulus for real improvements in the control of hardware variability. The research project focused on the development and documentation of a precision assembly methodology (including its application to a typical aerospace structure) and a thorough analysis of the organizational impacts of precision assembly, including recommendations for wide-spread implementation.

The research was performed in the Manufacturing Research and Development Organization within the Wichita Division of the Boeing Commercial Airplane Group. The research effort spanned a seven month period beginning in June, 1993.

One focusing assumption was made to maintain the research effort within a reasonable scope. The development of accurate manufacturing cost models and the analysis of the financial trade-offs implicit in the application of precision assembly processes was determined at an early stage to be beyond the limits of this research effort. In this regard, the majority of the research effort was focused on analyzing the *technical* and *organizational* feasibility of assembling aerospace structures without tools, and not necessarily proving the *financial* desirability of such approaches. The financial analyses which should precede any wide-spread implementation of the proposed methodology were not performed.

### **1.3 Structure of the thesis**

Section 2 of this thesis fully documents the causes of variation and its negative effects in the aerospace industry. It highlights one of the fundamental problems facing manufacturers in the commercial aircraft industry: variation in detail parts. Standard approaches to the control of hardware variability have not been effective in the aerospace industry for a number of reasons highlighted in Section 3. The fundamental argument of this thesis, namely that precision assembly methodologies are an integral part of any variability reduction effort, is also made in Section 3. Section 4 is the technical heart of the thesis and provides a detailed description of a methodology for precision assembly. A case study presented in Section 5 applies the proposed methodology to an aircraft floor structure and documents results and lessons learned from an actual implementation process.

Once a precision assembly methodology has been defined, the organizational implications of implementing that methodology in the production environment can be analyzed. Section 6 describes the implementation misalignments between existing organizational structures and the requirements of precision assembly. Section 7 then proceeds to make specific recommendations for how the organization and management systems of the aerospace factory should be modified to facilitate the introduction of precision assembly techniques. The thesis concludes with a summary of the research findings and recommendations for future work in Section 8.

### **1.4 Overview of the research findings**

This research effort demonstrated the technical feasibility of assembling aerospace structures without assembly tools. The successful implementation of precision assembly processes will require the identification and elimination of deficiencies in existing

fabrication processes. These fabrication process deficiencies may be addressed by purchasing new and more capable capital equipment, but more likely can be solved by operating existing machines with greater discipline. The key to precision assembly is continuous improvement in all fabrication areas, achieved primarily through a process of identifying and removing the causes of variability. The importance of gaining such deeper levels of process understanding will be a recurring theme in this thesis.

Precision assembly replaces traditional aerospace assembly techniques with one that clearly rewards reductions in hardware variability with improved quality, reduced cycle time, and (most likely) reduced cost. In this sense, precision assembly can provide the important focus required by hardware variability control programs and drive real progress in the reduction of variability. The development of new fabrication capabilities to meet the challenge offered by precision assembly can then be leveraged to better produce existing designs, directly addressing a critical market need by lowering unit costs. This increased level of process knowledge will also facilitate the development of superior next-generation product designs, providing a competitive advantage in the marketplace.

Although precision assembly may appear to be primarily a technological problem, the organizational impacts of precision assembly will be just as difficult (if not more difficult) to manage as the technological impacts. Significant organizational change will have to accompany the implementation of precision assembly if its postulated advantages are to be achieved. The barriers to the successful implementation of precision assembly are real and will only be eliminated through large scale change to organizational structures, policies, and people. Management must therefore assume responsibility for leading both technological and organizational change. The tendency for management to emphasize the search for technological solutions to manufacturing problems will address only a fraction of the implementation challenge. The real barriers to implementation are organizational, and management resources must be targeted in that direction.



## **Section 2. Variation and its effects on assembly productivity**

Bartelson (1993) estimated that the cost to produce aircraft doors could be reduced by 30% if assembly shops were provided with "perfect" parts (i.e., zero deviation from nominal). This section will describe the link between manufacturing process variability and unacceptably high levels of rework and waste in final assembly, both of which lead to cost penalties on the order of those documented by Bartelson. The negative effect of variation on assembly productivity will also be described in detail. The section concludes with one of the key arguments of this thesis: eliminating variation in detail parts is a point of significant leverage in the effort to reduce unacceptable levels of rejection and rework in assembly.

### **2.1 The cause of assembly problems is variation**

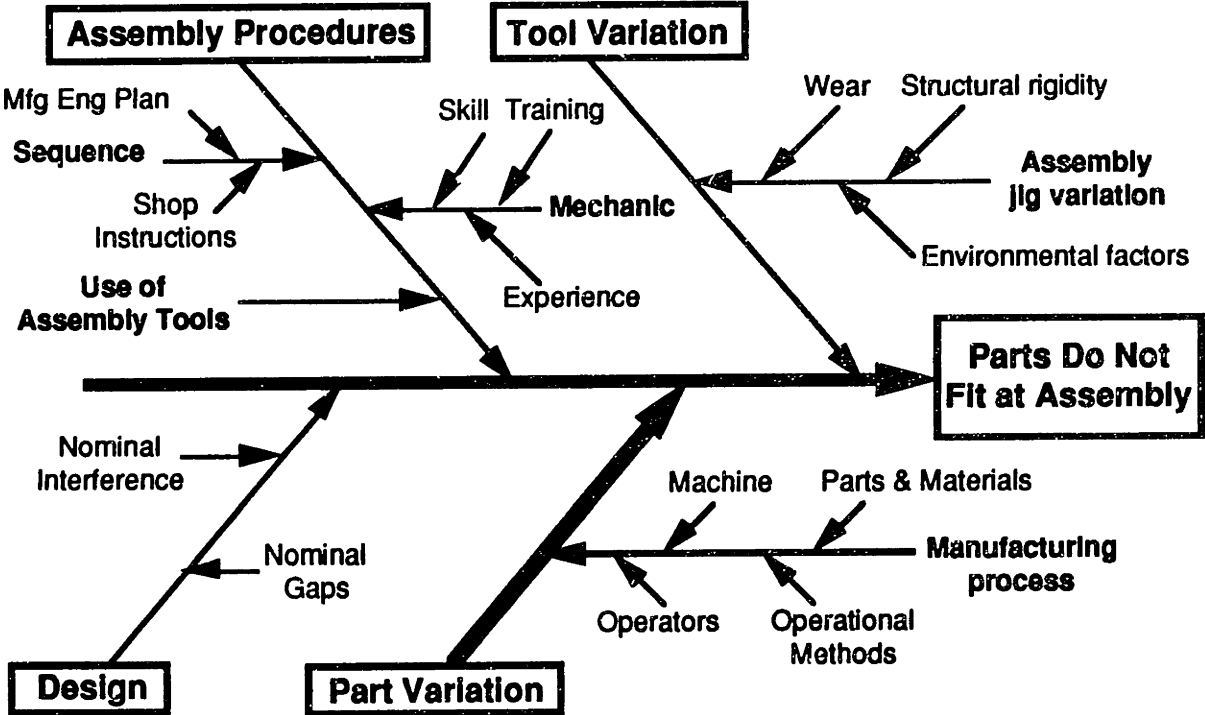
The source of most rejection and rework in the assembly of aircraft is variation. Variation in the nominal design, in the fabricated detail parts, in the assembly tooling, and in assembly procedures all lead to parts that do not fit on assembly. Figure 2.1 provides a pictorial summary of these four major causes of assembly problems in the aerospace industry (Shalon 1992):

- *Variation in nominal design.* Improper nominal design may cause nominal gaps (requiring shimming) or interferences (requiring trimming), leading to extra time and cost in assembly.

- *Variation in detail parts.* Material quality, fabrication temperature, operator methods and machine type will all affect the final configuration of the detail parts.

- *Variation in assembly tooling.* Temperature, structural rigidity, and the amount of wear over time will all introduce variation into the assembly tools required to establish product configuration.

- *Variation in assembly procedures.* Different operators with different experience and skill levels will invariably build the same structures in different ways. Variation in assembly procedures is also created by manufacturing planners who route identical assemblies through the factory in different ways.



Source: Shaion, 1992

Figure 2.1 The causes of assembly variation

Quantifying the relative importance of these four sources of variation in terms of manufacturing cost was not a major focus of this research effort. However, Section 2.3 below will describe how variation in detail parts is the point of highest leverage in

addressing assembly fit problems, primarily because detail part variation leads directly to variation in both tooling and assembly procedures.

## **2.2 The effects of assembly problems are significant**

*Variation causes rework.* Parts that do not fit on assembly must be hand-formed by skilled assembly mechanics into the correct configuration required by the assembly tools. Typical forms of rework include: shimming (addition of material to compensate for gaps), grinding (elimination of material to compensate for interferences), trimming (establishing the correct periphery of the detail part or assembly), and over-sizing fasteners (compensating for misaligned or poorly-drilled holes). The effects of variation require assembly mechanics to spend non-value-added time clamping (using everything from finger pressure to hydraulic clamps), strapping, hammering, filing, and hand forming parts into their designed configuration.

*Rework has many adverse effects.* Rework caused by variation has significant negative effects. Until the manufacturing organization recognizes that the following effects are avoidable, the assembly productivity dilemma will remain unaddressed.

- *Added assembly cost.* Beating parts until they submit to the correct configuration may produce acceptable aerospace structures, but the cost of using such labor-intensive assembly processes is unacceptable. In addition, variation in sub-assemblies must be accommodated at the assembly level, further increasing cost.

- *Added administrative costs.* Entire administrative staffs must be maintained to plan, schedule, manage, check, and document the performance of rework activities.

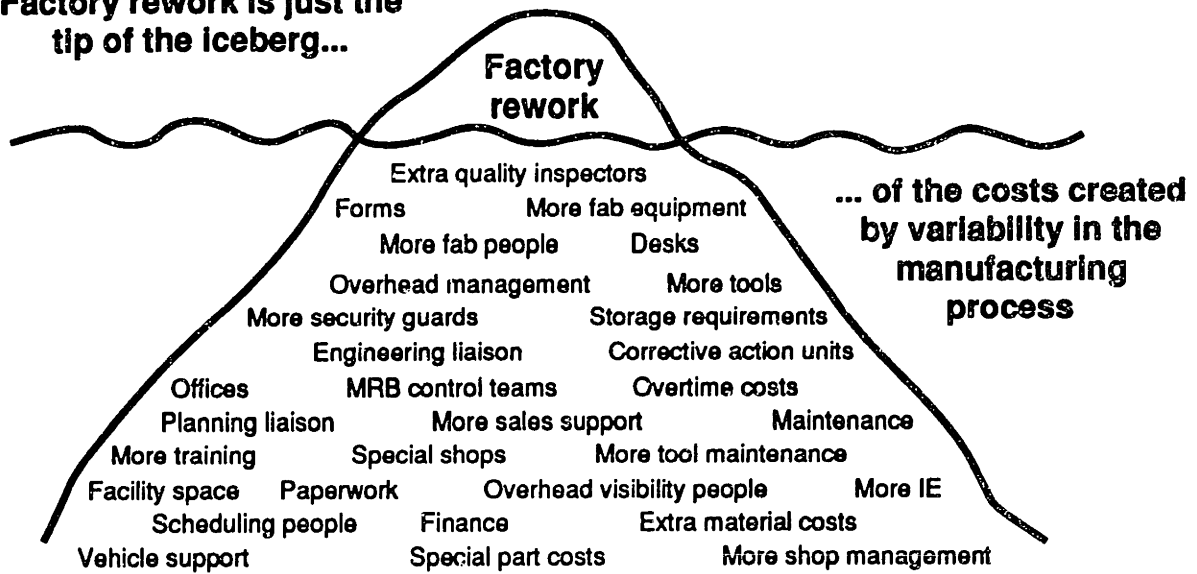
- *Increased part inventory.* "Just-in-case" inventories of parts must be maintained to buffer against standard levels of rework and rejection.

- *Increased tool inventory.* Assembly mechanics must maintain their own personal stocks of files, hammers, saws, clamps, drills, shims, etc.
- *Variable assembly times.* Different rework requirements on each airplane make factory scheduling difficult. The tendency to plan for the worst case leads to long inter-process buffer times, resulting in reduced cycle time. Significant amounts of straightforward, undocumented rework also tend to make scheduled assembly times longer than necessary.
- *Variable process flows.* Priority replacement orders and highly variable rework requests also make factory scheduling difficult. Many companies maintain an independent fabrication shop primarily to respond to such emergent high priority orders.
- *Reduced product quality.* The variable manner in which aerospace structures are assembled ensures that the product will not be delivered precisely as designed, with resultant drag and weight penalties due to surface dimpling, shimming, etc.
- *Residual stresses.* Restraining detail parts prior to fastening introduces stresses into the structure which degrade fatigue life. Structures assembled with such clamping techniques also have a tendency to "pop" into different configurations when removed from the assembly tools, thus creating additional fit problems for downstream assembly processes.
- *Low employee morale.* The ever-present nature of rework forces assembly mechanics to constantly develop quick-win solutions, all under tremendous time and budget pressure.

The costs directly associated with rework in the factory can be documented easily. The hidden costs of rework, however, are probably much greater than those costs classified as direct factory rework. Figure 2.2 depicts the source of much of the hidden costs of rework and rejection, and it is no surprise that the total annual bill for such activity is so large.



**Factory rework is just the tip of the iceberg...**



**Figure 2.2 The hidden costs of factory rework**

### **2.3 Eliminating variation in the detail parts is the point of highest leverage**

Looking back at Figure 2.1, two interesting observations can be made about the relative importance of the four sources of assembly problems. First, variation in the nominal design of both parts and tools has all but been eliminated through the use of 3D computer-aided design (CAD) systems. Nominal designs can now be digitally pre-assembled and modified on the computer prior to part or tool fabrication.

Second, and more important, *variation in detail parts is the primary cause of variation in assembly procedures and in assembly tools*. Variation in assembly procedures only comes into play if detail parts do not fit and the assembly mechanic must develop a specific "quick-win" assembly process. Deviations from preferred assembly processes are required by the challenges created by inconsistently variable parts. In terms of assembly tooling, the fundamental reason why tools exist is to accommodate detail part variation. If parts fit right the first time, the endless modification of the assembly

tools required to produce acceptable structures (which is itself a large source of variation) could be eliminated.

Variation must therefore be attacked at the point of greatest control: the fabrication of the detail parts. Detail part variation is the source of the problem which results in unacceptable levels of rework, rejection and waste. Many of the effects of variation documented above exist only because the parts, although manufactured within specification, are produced with some inherent level of variation. It is extraordinarily expensive to re-establish control over the configuration of the parts once that control has been lost through inaccurate fabrication processes. The only point where control can be re-established is in the assembly tool.

Real improvements in assembly productivity can be achieved if aerospace manufacturing organizations focus on the root cause of the problem and strive to eliminate detail part variability. This thesis will argue that precision assembly processes are a powerful means of achieving such reductions in detail part variability and the associated improvements in assembly productivity.

## **Section 3. The preferred approach to variability reduction**

This section will make the argument that an effective means of achieving significant reductions in hardware variability is to overhaul the assembly processes used in the aerospace industry. As described in the previous section, variability in detail parts and in assembly processes results in increased cost, decreased throughput, and lower quality. All lead to decreased customer satisfaction. The solution to detail part variability in the aerospace industry has proven elusive, however, even after the application of the hardware variability control (HVC) programs which have proven successful in other sectors. The implementation of precision assembly techniques, made possible with recent technological advances in design and fabrication processes, is offered as a means of providing focus for and improving the efficacy of existing HVC programs.

### **3.1 Typical HVC methods are of limited utility in the aerospace industry**

Variability reduction efforts in all industries typically fall into one of two categories: "inspecting quality in" by using tighter tolerances and increasing the number of inspections vs. root cause problem identification and elimination (Johnson 1988). Traditionally, the approach has been to tighten the tolerances on individual detail parts and increase the frequency of inspections. "Inspecting quality in" does little to address the underlying cause of the variability, but rather concentrates on identifying unacceptable parts and removing them from the manufacturing stream, often at great expense (see, for example, Deming 1982 or Shiba, Graham, and Walden 1993).

A better approach is to directly reduce variability through the improvement of both the design and manufacturing processes. To accomplish this goal, three objectives need to be achieved: the creation of robust designs, the development of capable manufacturing processes, and the existence of an environment which encourages continuous improvement

(Johnson 1988). Unlike their counterparts in other assembled goods industries, aerospace manufacturers have experienced difficulty in achieving substantial progress towards any of these three goals. The primary reason for the elusive nature of success with HVC is the existence of a number of conditions in the aerospace industry (to be described in detail below) which, taken together, make the aerospace industry different enough from other industries as to call into question the very applicability of "standard" HVC approaches.

### ***Difficulty in creating robust designs***

A robust design is one which is insensitive to the manufacturing process, customer use, and the environment. Because it may not be economical to remove or control some of the causes of variation in the manufacturing process, robust designs are a key component of any hardware variability reduction effort. The development of truly robust designs in the commercial aircraft industry is limited for the following reasons:

*Design optimization takes precedence over design robustness.* Design optimization has historically been the fundamental goal of product engineers in the commercial aircraft industry. Every non-essential pound on an airframe results in a significant financial penalty for the airline customer over the lifetime of the aircraft. There is a definite perception that standard techniques of robust design (slip planes, for example) have little to no applicability in the industry because of their implied weight penalties.

*Complexity of the design process makes the development of robust designs difficult.* A number of factors combine to ensure that the design process in the commercial aircraft industry will be very distributed and complex. The two most important are the large number of engineers required to design the sheer volume of parts in an airplane and the different engineering disciplines (stress, weight, materials, etc.) which must be included in the design of each structure. The distributed nature of the design process, where many engineers must collaborate in the design of even relatively simple structures, makes it very difficult to identify where a particular design should be made more robust.

*The reliance on assembly tooling makes robust designs superfluous.* The single biggest reason why robust design techniques have not been embraced by the commercial aircraft industry is the reliance within the industry on assembly tooling to determine actual product configuration. Complex and costly assembly tools are used not only to locate individual parts to each other, but also to locate subassemblies and assemblies to one another. Once the decision to use assembly tooling has been made, robust designs make less sense because the part-to-part alignments which robust design techniques aim to optimize will be completely controlled by assembly tooling. Even in the few cases where robust design techniques may be employed to *simplify* the fitting of parts into an assembly tool, the potential payoff in terms of reduced assembly time or improved product quality remains small.

#### ***Difficulty in developing capable manufacturing processes***

Capable manufacturing processes are ones that produce uniform, defect-free products that function well over their intended lifetime. This can only be achieved when the critical manufacturing parameters are known and the causes of variability are eliminated or minimized. Efforts to implement Statistical Process Control (SPC) in the aerospace industry have been less successful than predicted due to the following three factors:

*It is difficult to identify the high leverage processes worth controlling.* The first step in the implementation of any SPC program is to identify and prioritize the most critical processes in the manufacturing value chain. These critical processes are those that directly affect the key characteristics of the design, which are those attributes of the design where variation has the most adverse effect on form, fit, and function. Early industry efforts at identifying the key characteristics of product designs were beset with difficulty, and initial lists of key characteristics were either incorrect or so long as to make the designation meaningless. Without a clear understanding of where to target limited resources for maximum effect, SPC efforts will rarely produce the desired results.

*Keeping the production line moving takes precedence over SPC concerns.*

Historically, the basis of competition in the commercial aircraft industry has been meeting scheduled delivery dates. Initial enthusiasm for SPC has been tempered by a better understanding of the time required to effectively perform planned SPC activities. Manufacturing managers who were hired and promoted based on their ability to meet promised customer delivery dates are naturally reluctant to subordinate schedule concerns to the requirements of SPC.

*The safety net provided by assembly tooling leads to a less rigorous implementation of SPC.* Efforts to implement SPC in the aerospace fabrication shops are frequently accompanied by the thought that if the efforts are unsuccessful, the assembly shops will somehow find a way to "make the parts work." The safety net afforded by the assembly tooling and the expertise with which that tooling is used leads to a less rigorous implementation of SPC. Ironically, as assembly mechanics perform their jobs better, they tend to better hide the negative effects of detail part variability.

***Difficulties in fostering an environment of continuous improvement***

Continuous improvement requires tireless attention to design and manufacturing processes throughout the life of the production system. The topic of continuous improvement can be broken down into its two major components: efforts focused on improving the design itself, and efforts focused on improving the execution of the design in the manufacturing environment. The aerospace industry has historically practiced the latter, if for no other reason than the average production life cycle of a commercial transport can span as much as 25 years. Incremental developments in process technologies are fielded on older designs in an effort to remain cost and technology competitive with other players in the industry. Unfortunately, the typically low production rates of commercial aircraft provide infrequent opportunities to design and perform experiments in an effort to make large improvements in the manufacturing process.

Industry efforts at continuous improvement rarely extend, however, into the design arena. Once completed, aerospace manufacturers regard their FAA-certified designs as a virtually untouchable asset to be executed by the manufacturing organization for as long as the market will permit. Any incremental efforts to modify the design for ease of manufacturing are discouraged primarily because of a perceived cost penalty associated with redesign and recertification, and secondarily because the original design groups are rarely intact. This reluctance to revisit and improve the design prevents the full leveraging of new manufacturing capabilities.

For all of the reasons outlined above, the implementation of HVC in the aerospace industry in general has been less successful than desired. Part of the problem is created by the use of an assembly process which does not reward reductions in detail part variability. Another part of the problem centers on the complexity of commercial aircraft design and manufacturing processes and the difficulty inherent in trying to comprehend all of the factors influencing final product configuration. The final part involves the systemic forces at work in the factory which have acted to limit the effectiveness of variation reduction efforts. Quite simply, active participation in variation reduction programs has been limited by the traditional and seemingly contradictory emphases on meeting budget and maintaining schedule. Factory planners, manufacturing engineers and production personnel are not rewarded (or given sufficient incentive) to develop, execute, and maintain effective variation reduction programs. Whenever time or budget pressures mount, HVC programs tend to be sacrificed in the manufacturing organization for the more traditional objectives of cost and schedule.

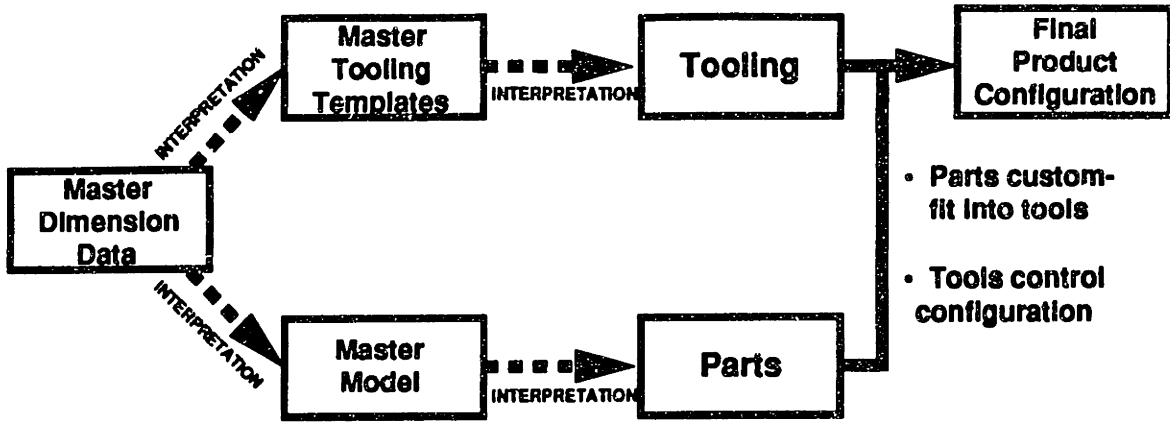
### **3.2 Recent technological advances have enabled new, more effective approaches to HVC**

Recent advances in design and manufacturing technologies will permit the development of more effective approaches to eliminating detail part variability. It is instructive to first understand the traditional aerospace design and manufacturing processes, and then to document the recent improvements to those processes achieved as a direct result of the use of computer-aided design (CAD) systems. It is the introduction of CAD tools which will address many of the systemic problems which have undone previous HVC efforts. In fact, the method to address the problems caused by detail part variability proposed in the next section depends heavily on CAD systems which permit designers to rapidly model the effects of variation to effectively target variation reduction efforts.

#### ***The aircraft manufacturing process for products designed prior to the widespread use of CAD systems***

Figure 3.1 provides a simplified overview of the aircraft manufacturing processes for products designed prior to the introduction of CAD systems (Anderson, 1993). Two items are worth noting in the diagram. First, the transfer of the product design from the engineering to the manufacturing community passes through a number of subjective translation steps which are themselves large sources of variation. Design engineers interpret the Master Dimension Data (MDD) and create master models, which are then interpreted a second time by a second set of engineers responsible for the specific configuration of detail parts. Those parts are then mated to other parts in the assembly tooling, which itself has undergone a similarly inaccurate two-step interpretation process in the tooling organization. Controlling variation in an environment where even the nominal product configuration is unclear and subject to interpretation (i.e., is the "correct" product configuration defined by the tools or by the parts?) is virtually impossible.





- Tooling controls final product configuration
- Product accepted to the tooling, not to the original Master Dimension Data
- Numerous interpretation steps are a key source of variability
- Custom-fit process masks the effects of detail part variability

**Figure 3.1 The manufacturing process for products designed prior to the introduction of 3D CAD systems**

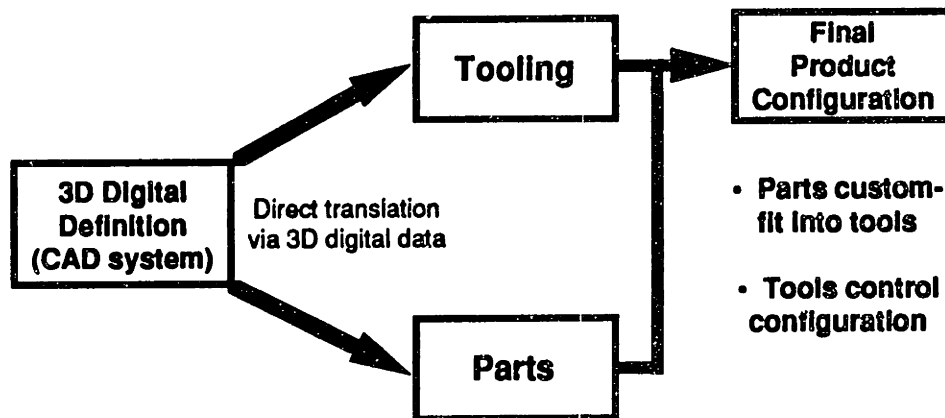
Second, the final product configuration is controlled entirely by the assembly tooling. As mentioned earlier, the negative effects of detail part variability are easily hidden as expert craftsmen shim, hammer, and grind highly variable parts into the correct configuration.

***The aircraft manufacturing process for products designed after the widespread use of CAD systems***

Figure 3.2 provides an overview of the aircraft manufacturing processes for products designed after the introduction of 3D CAD systems. The introduction of CAD systems has eliminated the inaccurate translation processes required previously during the transfer of the design into the manufacturing environment. The 3D digital product definition allows both part and tool designers to work directly from the exact same design information. More importantly, the 3D solid models allow part and tool designers to visualize in three dimensions the relationship between a given part and all mating parts and/or assembly

tools. CAD systems also facilitate a systems engineering perspective by allowing design engineers to rapidly access the designs of other parts of the product which may either affect or be affected by their own designs. The addition of variation modeling packages into the CAD environment will eventually enable designers to verify their designs under both nominal and variable conditions. Finally, the data from the solid models can be downloaded directly to computer numerically controlled (CNC) machining centers for the consistent, accurate production of detail parts.

Now that the 3D CAD systems have been successfully incorporated into the design and manufacturing environment, all that remains is to understand how best to leverage that investment in eliminating detail part variability. While the introduction of the 3D CAD systems will facilitate existing efforts in controlling hardware variability, many of the systemic obstacles identified in Section 3.1 still remain. The next section proposes a method of using these CAD systems and current manufacturing capabilities to drive HVC efforts by radically altering the single biggest obstacle to real change: the current assembly process.



- 3D CAD system removes 2 separate processes of interpretation
- Product still accepted to the tooling, not to CAD system data
- Custom-fit process masks the effects of detail part variability

**Figure 3.2 The manufacturing process for products designed after the introduction of 3D CAD systems**

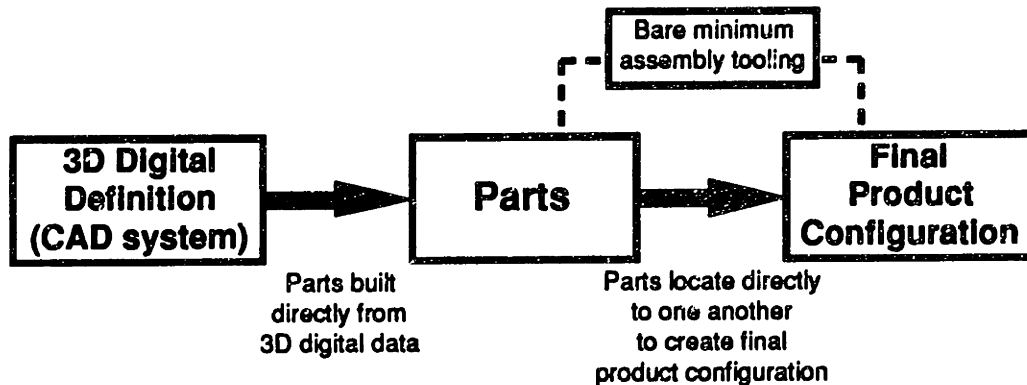
### **3.3 Precision assembly as the next paradigm in aerospace manufacturing**

The high costs and long lead times which occur in part due to detail part variability may be better addressed through the adoption of precision assembly techniques. Many of the roadblocks encountered by present HVC efforts will exist as long as aerospace manufacturers rely on assembly tooling to determine the configuration of their products. Although continuing to execute the current HVC program will result in some tangible benefits, breakthrough improvements in assembly time and cost will never occur as long as the baseline process remains so labor and capital intensive.

Very simply, *the goal of precision assembly is to eliminate the use of tooling in the aircraft assembly process.* Precision assembly replaces traditional aircraft tooling concepts by placing all of the configuration-controlling information directly into the detail parts. Parts will be located directly to one another, without the use of assembly tools, in exactly the configuration specified by the designer. Existing fastener locations will be used as index points from which the position of two parts relative to one another will be determined. The use of assembly tools will be reserved only for those very complex assemblies where intricate part stack-ups are coupled with precise tolerance requirements. Figure 3.3 is a pictorial description of an aircraft manufacturing process which uses precision assembly techniques. The specific methodology for implementing precision assembly processes is discussed in detail in Section 4.

Although an innovative approach in the aerospace industry, precision assembly techniques have been applied for many years in the auto and consumer electronics industries (see Held 1993, for example). HVC efforts have been more successful in those industries because the bottom-line impact of variation is so much clearer, especially when an assembly line must be stopped in order to correct an installation problem caused by variation. Attempting to extrapolate lessons from the implementation of HVC programs in industries with substantially different assembly processes is problematic. Only when the

aerospace industry adopts assembly processes similar to those used in other industries will it be able to achieve the dramatic improvements in cost, throughput, and quality seen in those industries. Indeed, the adoption of precision assembly processes in the aerospace industry will enable aerospace firms to leverage, for the first time, the years of HVC experience found in other industries.



**Figure 3.3 The vision of precision assembly**

### **3.4 Using the implementation of precision assembly techniques to drive the solution to the detail part variability problem**

Implementing precision assembly will have direct and immediate results in terms of reducing assembly cost and time. But the real payoff to precision assembly may very well be the focus it provides for factory-wide hardware variability control programs.

The elimination of assembly tooling *requires* the precise manufacture of detail parts. In some sense, the individual detail parts are now themselves the assembly tools. Controlling the variability in detail parts becomes even more important in the precision assembly factory because whatever variation exists in the detail parts will be translated directly into the final assembly. Unacceptable variation in detail parts will lead to unacceptable variation in final assemblies and subsequent rejection of that assembly.

The systemic forces of the factory which have acted to prevent real progress towards HVC can now be harnessed as a driver of change. The planners, financial experts, and shop supervisors who were motivated to sacrifice HVC for the sake of more traditional objectives now are unable to satisfy these same traditional objectives (meeting schedule, meeting budget, etc.) *without* effective variability control programs. Precision assembly therefore drives variability reduction efforts with a much sharper focus than efforts to date. Rather than continuously improving an antiquated and inefficient manufacturing process, implementing precision assembly will provide the opportunity for breakthrough improvements in the manufacture of aircraft.

### **3.5 Limitations in the applicability of the proposed method**

The importance of computer-aided design systems to the successful implementation the proposed precision assembly methodology cannot be overstated. The widespread use of CAD systems has enabled everyone from designers to tool engineers to manufacturing engineers to work from a common, fully-dimensioned drawing of the product. Precision assembly processes will fail without a common 3D digital product definition which can be passed between the design and manufacturing communities. The many interpretations and inaccurate translations performed between the design and production environments introduce variation into the very definition of the product which, when coupled with unavoidable manufacturing variability, destroys any chance of success with a tool-less assembly approach. An analysis of the stack-up of tolerances in an assembly, which might allow an engineer to create a design more robust to the effects of manufacturing process variability, cannot be performed efficiently without 3D solid models.

If precision assembly techniques require products with a 3D digital definition, how should an aircraft manufacturer approach the problem of detail part variability on product lines designed prior to the introduction of complete CAD systems? One potential approach

is the investment in new assembly technologies which permit the rapid, accurate assembly of detail parts with current levels of variability. Some preliminary work in this regard has shown that assembling large fuselage panels using such techniques can result in increased throughput and higher levels of quality (Anderson 1993). Another approach, applicable to products designed before and after the introduction of CAD systems, may be the use of high speed machining techniques to combine into a single structure what once were many different parts. This approach bypasses the negative assembly effects caused by detail part variability by eliminating many of the constituent detail parts. The choice of one approach over another should be based on factors such as cost, manufacturing process capability, and design requirements (configuration, performance, weight, etc.).

This thesis does not intend to propose that the use of precision assembly techniques is the only way to mitigate the problems caused by variability in detail parts. The methodology to be proposed in this thesis is *not* a variability panacea for all aircraft products. Although it appears to hold great promise in the battle to reduce hardware variability and its effects, it is limited in its scope of application to those products with 3D digital definitions. The points of maximum leverage in reducing variability on older generation products are different and will require different techniques. To prevent confusion, the remainder of this thesis will be limited to the implementation of precision assembly techniques on those products digitally-defined in a CAD environment.

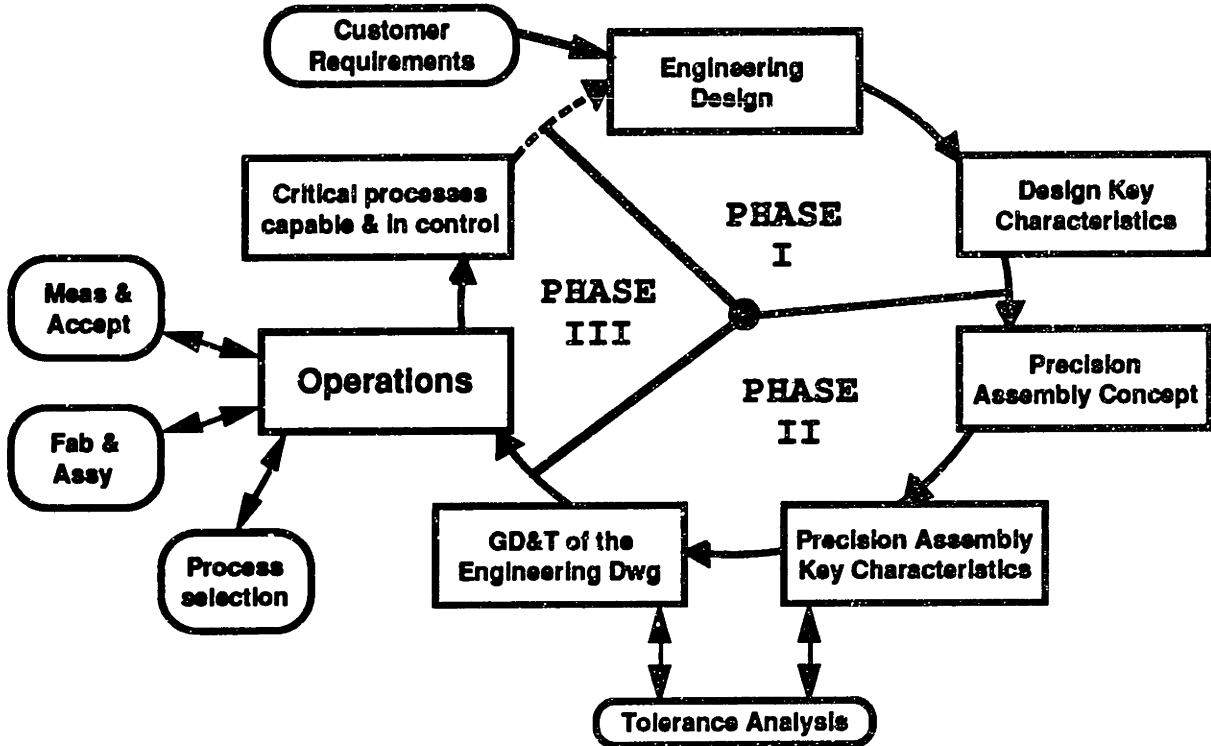
## **Section 4. The precision assembly methodology**

This section is designed to provide a detailed description of the proposed precision assembly methodology. This section also includes a comprehensive list of the benefits realized through the successful use of the proposed methodology. The implementation of precision assembly is divided into three phases: product definition, definition of the precision assembly concept, and execution of the precision assembly concept. Figure 4.1 provides a top-level view of the precision assembly process, including the three phases and their constitutive activities. Phase I, the product definition phase, will highlight the engineering changes required by the downstream use of precision assembly techniques. Phase II describes the development of the precision assembly concept and the information requirements necessary to communicate the details of the concept to the manufacturing organization. Phase III, the execution of the precision assembly concept, details the impact of precision assembly on each part of the factory. This section will conclude with an analysis of the tactical and strategic advantages achieved through the implementation of precision assembly.

Throughout this section, a typical aircraft floor structure will be used to illustrate, in general terms, the concepts presented. A more detailed case study of the application of this precision assembly methodology to an aircraft floor structure will be provided in Section 5. The case study is intended to supplement this section's generic methodology and document the specific trade-offs required by precision assembly. The precision assembly concept will be defined in full detail, and results from the implementation of that concept will be provided.

Before describing the methodology in detail, it may be instructive to once again define exactly what is meant by precision assembly. *The goal of precision assembly is to eliminate the use of tooling in the aircraft assembly process. Precision assembly replaces traditional aircraft tooling concepts by placing all of the configuration-controlling*

information directly into the detail parts. Parts will be located directly to one another, without the use of assembly tools, in exactly the configuration specified by the designer. Existing fastener locations will be used as index points from which the position of two parts relative to one another will be determined. The use of assembly tools will be reserved only for those very complex assemblies where intricate part stack-ups are coupled with precise tolerance requirements.



**Figure 4.1 Implementation methodology for precision assembly**

#### **4.1 Phase I: Product definition**

The transition to precision assembly places a number of new requirements on the engineering definition of the product. Phase I of the implementation process centers on



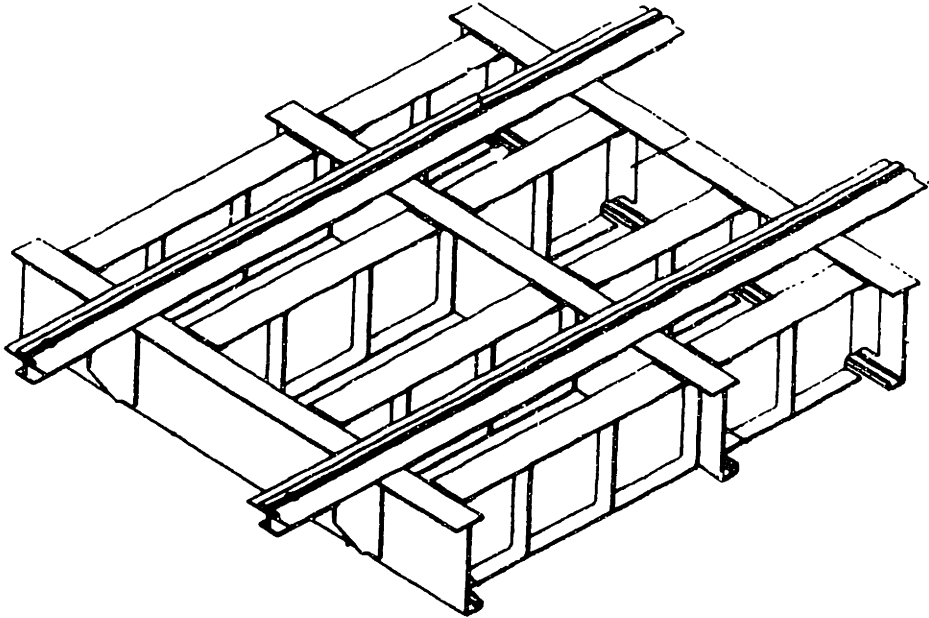
the development of the engineering design and the key features which will enable the downstream use of precision assembly techniques.

*Customer requirements.* The first step in the creation of any product design, whether it be a simple consumer product or something as complex as an airplane, is to develop a comprehensive list of customer requirements and desires. Typical customer requirements for the floor structure of an aircraft would cover areas such as floor geometry and strength, part interchangeability/replaceability, and ease of maintenance. The implementation of precision assembly places no additional requirements on the process in which customer needs are collected and provided to the design community. This portion of the design process is mentioned here only for the sake of completeness.

*Engineering design.* The precision assembly methodology proposed in this thesis requires a three-dimensional digital definition of the product. In the aerospace industry, only those products digitally-defined in the CAD environment are good candidates for precision assembly. Why? Because using detail parts to control the configuration of the aircraft places extraordinary requirements on the accuracy of individual parts and on the way those parts assemble to form a complete structure. Figure 4.2 is the 3D digital definition of a subsection of a typical aircraft floor structure. Although not included in Figure 4.2 for the sake of clarity, all dimensions are an integral part of the drawing file.

Pre-CAD system designs placed only ballpark tolerances ( $\pm .030$  inches) on all detail parts because assembly tooling was relied upon to control the configuration of the final structure. The manufacturing support systems which have been developed to produce those early designs are simply not currently capable of providing parts accurate enough to make precision assembly work. The subjective and inaccurate interpretation processes (described earlier in Section 3 and in Figure 3.1) used to translate from the nominal design to the manufacture of individual parts and tools are the single biggest reason why

precision assembly cannot be implemented on earlier designs. Further, the rapid iteration of various part-to-part coordination schemes required to develop a successful precision assembly concept would be virtually impossible to accomplish in a world of non-dimensional drawings, master models, and master tooling templates.



**Figure 4.2 3D digital definition of the aircraft floor structure**

*Key characteristics of the design.* Key characteristics are those features or attributes of an installation, assembly or detail part where deviation from nominal has the most adverse effect on fit, performance, and service life. Key characteristics are vehicles for communicating to the manufacturing organization which features of the design are most critical. A typical key characteristic for the floor structure pictured in Figure 4.2 would be that the seat tracks, to which all of the passenger seats will be mounted, must be parallel throughout their entire length within  $\pm .030$  inches. An accurate list of key characteristics greatly facilitates precision assembly because it allows the developer of the precision assembly concept to focus his attention on a reasonable number of design attributes. By limiting the scope of the problem to a reasonable level, key characteristics permit the rapid and efficient iteration of alternative precision assembly concepts subject

to only the most important design constraints. This process will be described in much more detail during the Phase II discussion below.

*Summary.* The two most important building blocks for precision assembly are a 3D digital product definition and a thorough list of design key characteristics. As most aerospace manufacturers have already incorporated computer-aided design systems and key characteristics into their product definition processes, the precision assembly requirements noted here represent little additional effort for current generation products. Implementing precision assembly on products without good lists of key characteristics would be difficult. Implementing precision assembly on products without 3D digital definitions would be virtually impossible.

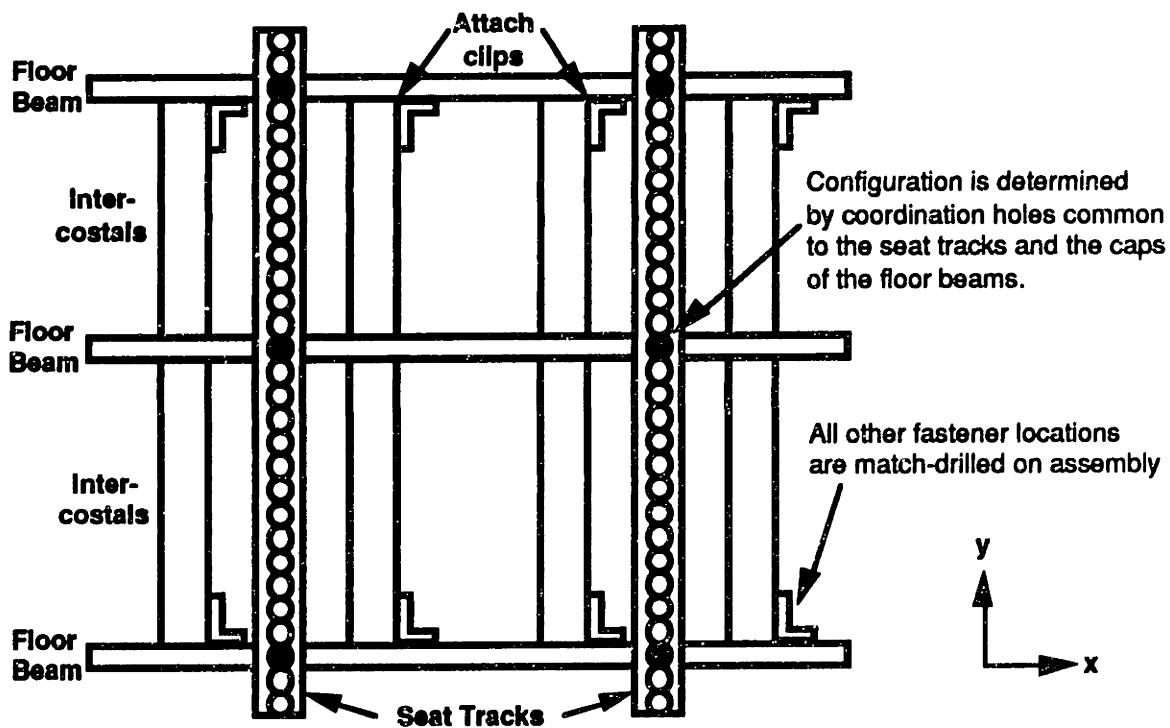
#### **4.2 Phase II: Definition of the precision assembly concept**

The complete definition of the precision assembly concept is the second phase of the methodology shown in Figure 4.1. Beginning with the engineering definition of the final form of the product, this phase develops the vision of how the product will go together with minimum use of assembly tooling, and then moves backward through the manufacturing process to place the requirements for precision assembly into each of the individual detail parts. The goal of this second phase are detail part tolerances and specifications which will allow those parts to be assembled to each other without the need for assembly tooling.

*Precision assembly concept.* The first step in the development of the precision assembly concept is to construct a top level vision of how the parts will be assembled. The precision assembly concept will highlight those parts of the design which must be controlled in order to make the concept work. It is critical to develop the entire concept,

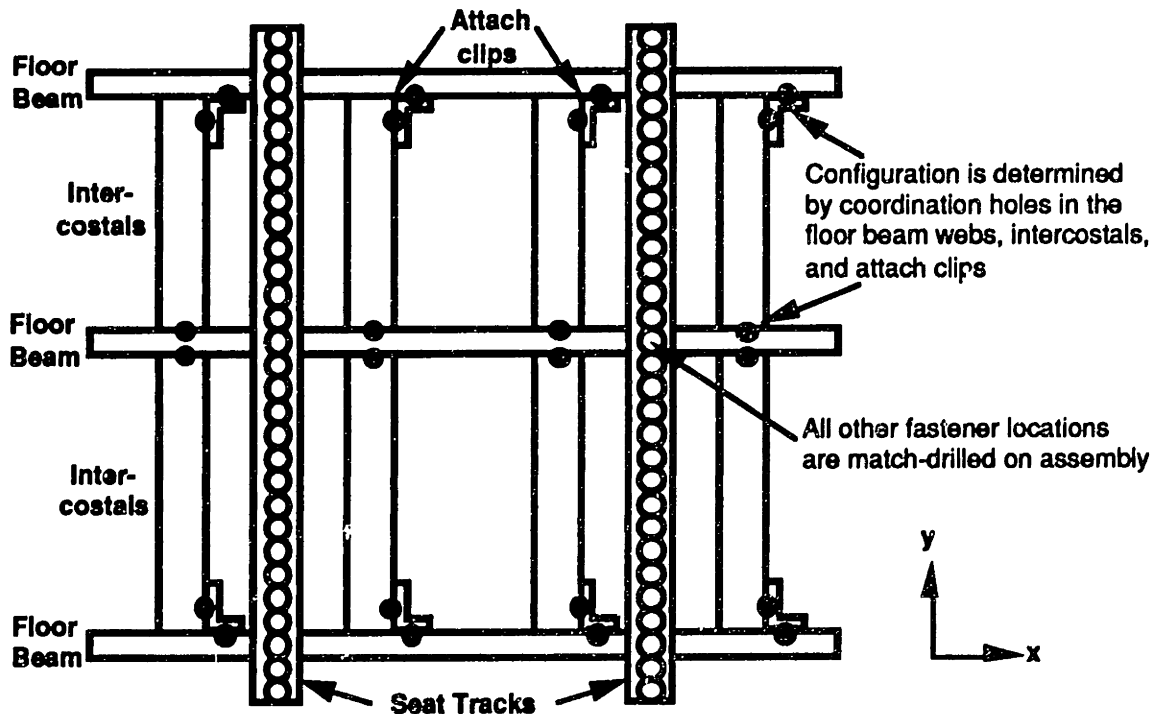
at least at a top level, at the very outset because different concepts will place different requirements on the same components of the structure.

Figure 4.3 provides one possible precision assembly concept for the floor structure discussed earlier. In Figure 4.3, the spacing between the floor beams in the y direction will be controlled by matching coordination holes in the seat tracks and in the floor beam caps. As long as the coordination hole locations in the seat tracks are accurate, the floor beams will be located at their correct positions in the y dimension. The spacing between the seat tracks in the x direction will be controlled by these same coordination holes. As long as the coordination hole locations in the caps of the floor beams are accurate, the seat tracks will be located at their correct positions in the x dimension. The entire structure can thus be assembled using only the information contained in the detail parts (i.e., the location of the coordination holes in the floor beam caps and in the seat tracks).



**Figure 4.3 One possible precision assembly concept: Using the seat tracks to determine floor beam spacing**

It is not difficult to see, however, how different precision assembly concepts will place different requirements on the same parts of the structure. Figure 4.4 shows how the same structure can be built using an entirely different process. In this case, the configuration is controlled not by coordination holes in the floor beam caps and seat tracks, but by coordination holes in the floor beam webs, intercostals, and attach clips. The different concepts place very different accuracy requirements on the intercostals and the attach clips. In the concept pictured earlier in Figure 4.3, the intercostals and attach clips are not used to set the configuration of the structure. Their attributes are thus less important than the positions of the coordination holes in the floor beams and seat tracks. The intercostals and attach clips can be match drilled on assembly once the floor configuration has been set by the floor beams and the seat tracks. In Figure 4.4, the assembly concept requires much more accuracy of the intercostals and the attach clips because they are essential in properly spacing the floor beams relative to each other.



**Figure 4.4 Another possible precision assembly concept: Using the intercostals and attach clips to determine floor beam spacing**

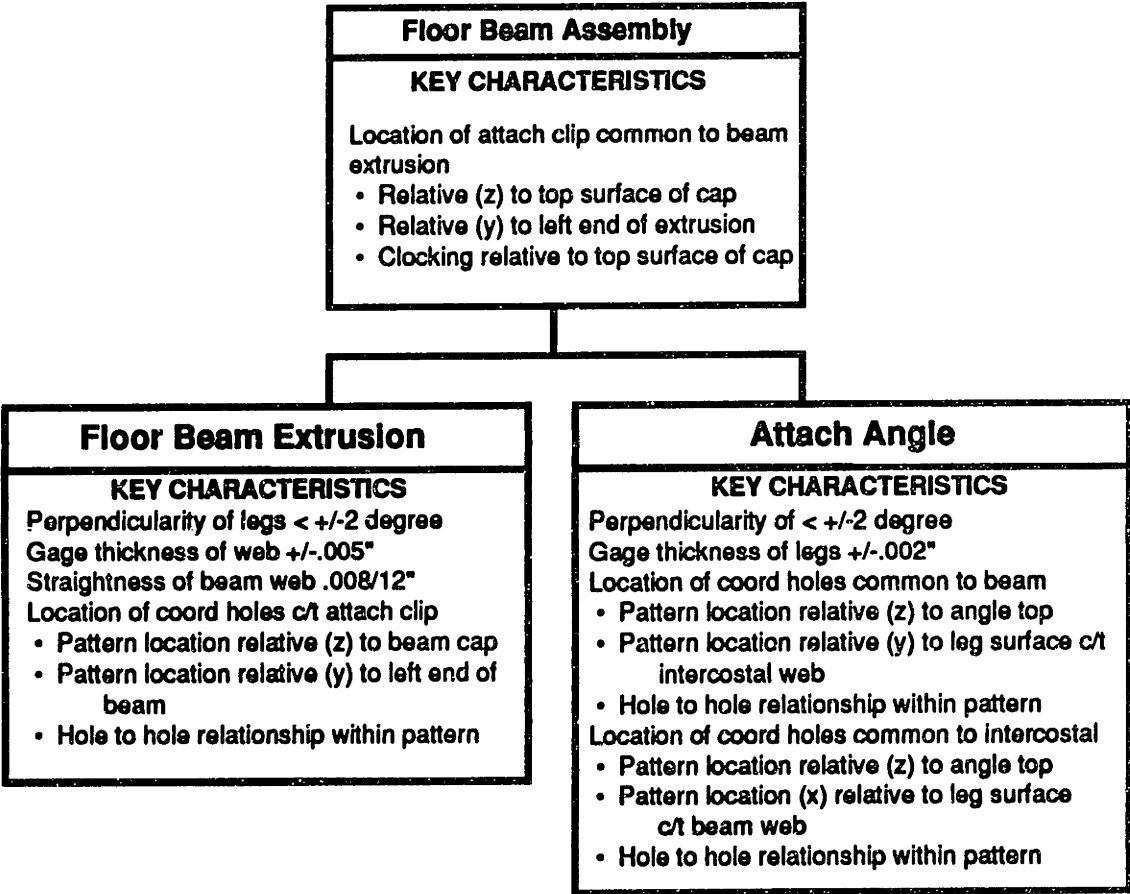
The process of assigning tolerances to individual detail parts can not begin until the entire precision assembly concept has been developed. In the example provided in Figures 4.3 and 4.4, it is clear that the precision with which individual parts need to be manufactured changes as a result of the precision assembly concept selected. Selecting one precision assembly concept over another should be based on factors such as cost, manufacturability of detail parts, ease of assembly, and interchangeability requirements. In this regard, the concept described in Figure 4.3 is probably preferable because it requires fewer coordination holes to set the final configuration of the structure.

*Precision assembly key characteristics.* Once the precision assembly concept has been identified, the design should be analyzed to determine those aspects of the structure where variation will have the most adverse effect on assembly fit. Precision assembly keys are generated in a similar manner to the previously mentioned key characteristics of the design, yet there is a critical difference. Key characteristics of the design identify what is important from the perspective of the functionality of the design. Precision assembly key characteristics identify what is important from the perspective of the functionality of the assembly process. The two lists of key characteristics may be different from one another because they serve two very different purposes.

Key characteristics should be identified for every detail part, subassembly, and assembly for which the precision assembly concept will be implemented. The process of identifying key characteristics should begin at the final assembly level and proceed to flow down to the individual detail parts. Figure 4.5 shows such a flow down of key characteristics for a relatively simple floor beam assembly. It documents not only the key characteristics of the completed floor beam assembly, but also the key characteristics of the two types of detail parts (beam extrusion and attach clips) which make up the floor beam assembly. This information will be critical when performing the tolerance analysis

and moving from qualitative assessments of importance to quantitative assessments (i.e., specific tolerance call-outs).

A few final observations should be made about the identification of key characteristics. First, the identification of key characteristics is an invaluable tool in understanding not only the intent of the design, but the functionality of the specific precision assembly concept. Identifying keys is therefore best done in a cross-functional environment where those who have a stake in the different segments of the manufacturing process are permitted input into the design of the precision assembly concept. This has the added benefit of leveraging the diverse set of skills present throughout the



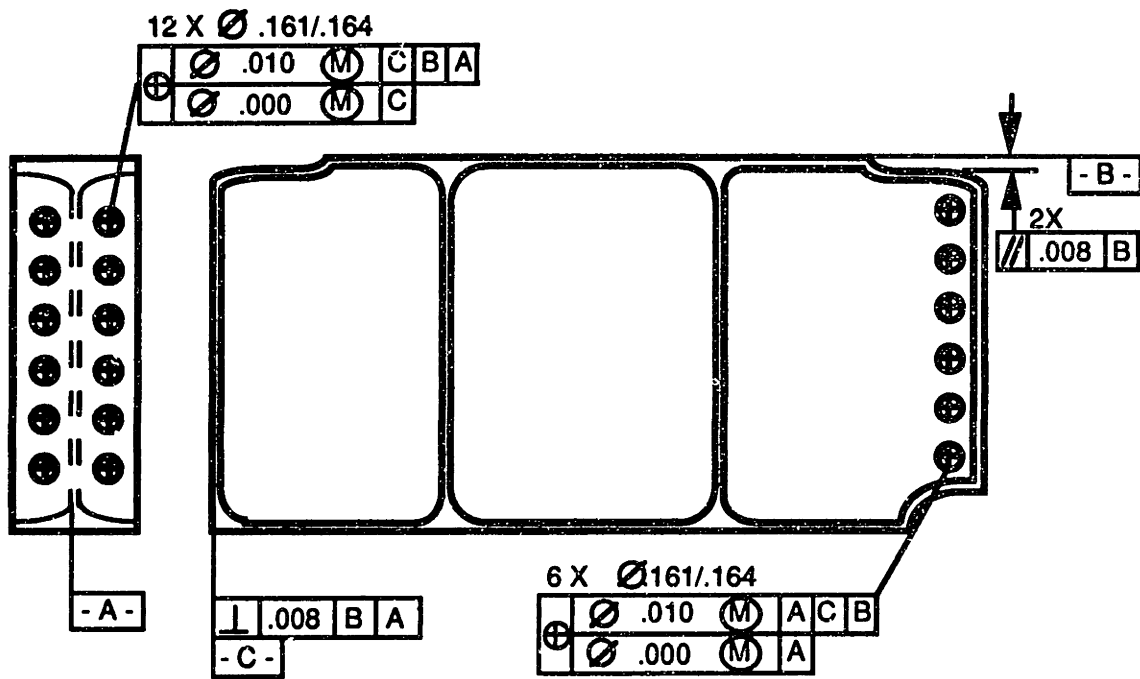
**Figure 4.5 Typical flow down of key characteristics**

organization in the development of the precision assembly concept. Second, the level of detail in any list of key characteristics is critical. A list which provides only general information (i.e., contour is critical, hole location is critical, etc.) is of little use in determining quantitative values during the tolerance engineering process. On the other hand, overly-comprehensive lists of key characteristics are not only costly to develop, but do not provide the focus of a well-developed list.

*Geometric dimensioning and tolerancing of the engineering drawing.* This is undoubtedly the most important step in the implementation of precision assembly techniques. By their very nature, the tolerances placed on an engineering drawing are an instruction from the designer to the manufacturer about how inaccurately the detail parts may be fabricated and still satisfy the precision assembly requirements. The tolerances must be tight enough to guarantee acceptable assemblies, but not too tight as to make the fabrication process unduly difficult and/or expensive. Figure 4.6 is an engineering drawing of a typical intercostal, including the tolerances required by precision assembly.

The tolerances on the engineering drawing will also be the historical record of the decisions made during the development of the precision assembly concept. As the probability of getting more than one opportunity to take the detailed systems view of the structure required by the precision assembly methodology is low, it is essential that the tolerance engineering process be thorough and accurate. Like the assembly tooling in today's manufacturing environment, the tolerances on the engineering drawing will become the primary determinant of product configuration. If the tolerances are specified correctly, and if the detail parts are fabricated within those tolerances, assembling the parts without assembly tools should be straightforward.





**Figure 4.6 Geometric dimensioning and tolerancing of the engineering drawing**

The existence of the 3D digital definition of the product allows a number of powerful computer tools to be brought to bear. One of these tools is the digital preassembly package used with great success on the 777 aircraft program (Aviation Week and Space Technology 1994). Digital preassembly (DPA) software packages are used to verify the nominal definition of detail parts and assemblies. DPA can check for obvious problems like gaps and interferences in the nominal definition of the product. The use of digital preassembly has significantly reduced the number of engineering change orders caused by improper nominal design.

Digital preassembly tools which only deal with nominal part dimensions, however, are not able to provide much assistance in the detailed tolerance engineering effort required by the precision assembly process. In order to properly tolerance an engineering drawing, the designers of the precision assembly concept must be able to rapidly

ascertain the effects of real world manufacturing variation on their concepts. In other words, a computer tool is required which can repetitively build aerospace assemblies from detail parts with "typical" amounts of variation, where "typical" is determined by the capabilities of the manufacturing processes used to create those parts. Such a statistical preassembly (SPA) tool can thus simulate hundreds of assembly build processes in the computer environment and rapidly help the designer determine the optimal specifications for the different components of the structure.

A number of firms are working to develop statistical preassembly software packages which can be used to predict the effects of manufacturing process variation on final product form, fit, and function. These packages will eventually be linked to computer-aided design systems and permit the designer to rapidly iterate his design under both nominal (DPA) and real (SPA) conditions. The potential applications for such variation analysis tools are:

- Statistical Preassembly (SPA) based on actual tolerances
- Predicting the impact of individual part variability on an entire structure
- Analysis of tolerance buildup in a structure
- Location and percent contribution of variability in a structure
- Determination of process capability requirements
- Analysis of sensitivity to different assembly processes

The benefits of performing statistical preassembly are clear. Statistical preassembly (SPA) assists the designer in the development of a structure's key characteristics. On the Boeing Company's 777 program, lists of design key characteristics were developed without the use of such analytical tools. Deficiencies in the list of keys were only identified once fabrication and assembly began (Anderson 1993). SPA also allows the current capabilities of the manufacturing organization to be used in the product design process, as well as helping it more effectively target future capital investments. Specific assembly problems can be debugged more effectively with a SPA tool, and proactive

steps can be taken to prevent detail part variation from affecting the form, fit, and function of the entire assembly.

Statistical preassembly software packages are not without their limitations, however. Typical limitations include: the inability to accurately model the flexibility of aluminum structures, the inability to model compliance during the assembly process, and the inability to allow two parts to position a third using a real world, best fit approach. Such programs typically use a single reference datum and position all subsequent parts off of that one primary datum or part.

Although presented here and in Figure 4.1 as the final step in the definition of the precision assembly concept, the tolerance engineering process is best performed concurrently with the development of the concept and its key characteristics. Many of the learning loops which should be included in Figure 4.1 are omitted for the sake of clarity. For example, the tolerance engineering process may very well identify shortcomings in the precision assembly concept, requiring modifications to that concept. In addition, the tolerance engineering process may also help identify important characteristics of the structure which were not initially considered key.

*Summary.* The end result of Phase II of this precision assembly methodology will be a set of dimensioned drawings for the component parts of an assembly which, when fabricated to the required tolerances, will permit the assembly of the structure without assembly tools. A key part of the methodology is that the precision assembly concept is generated via a flow down of requirements from the assembly level to the individual detail parts. The accurate definition of key characteristics and the tolerancing of detail parts can only occur once the top level precision assembly concept is known. Eventually, Phase I and Phase II of the precision assembly methodology should be a seamless process where an integrated product team develops both the product and the precision assembly concept at the same time. The product design and precision assembly concept can then

be checked and modified as needed based on the results of a rigorous tolerance engineering process.

#### **4.3 Phase III: Execution of the precision assembly concept**

Once the definition of the precision assembly is complete and communicated via engineering drawings, detail parts must be fabricated and assembled into the final structure. Phase III of the precision assembly methodology involves the important (and perhaps iterative) steps of selecting the right manufacturing processes, fabricating and assembling according to plan, and measuring the structure throughout the build process. The goal of Phase III is a complete set of manufacturing processes consistently capable of meeting the tolerances required by precision assembly structures.

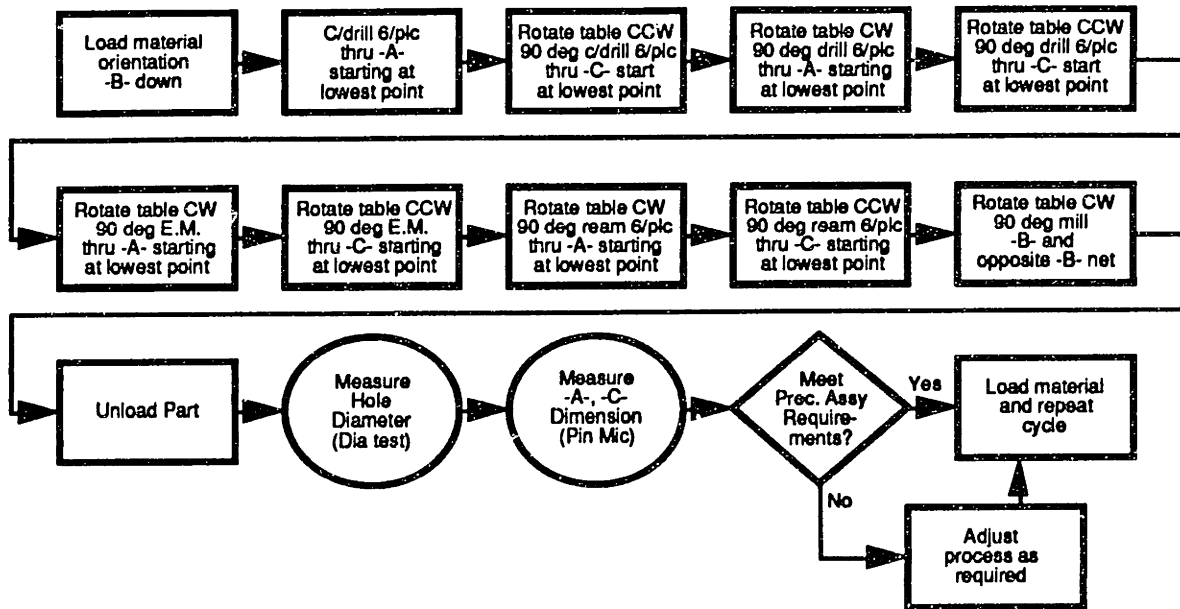
*Selecting the appropriate manufacturing process.* Precision assembly will almost certainly require the use of more capable manufacturing processes. The first step in selecting appropriate processes is to ascertain if current processes are capable of meeting the tolerances required by the precision assembly concept. If the process capability does exist in-house, fabrication of the detail parts can proceed. The manufacturing engineering organization will have to pay particular attention to factory capacity issues created as detail parts destined for precision assembly processes are shifted from less capable to more capable machines.

If existing manufacturing processes are not capable of meeting the required tolerances, or if the factory does not currently have the required capacity on its most capable machines, the problem becomes a bit more challenging. The manufacturing organization should then perform a trade-off study between two alternative courses of action: developing a plan on how to either acquire the required capability, or redefining the precision assembly concept and tolerances. The most obvious solution, when faced

with a capacity problem on highly capable machines, is to purchase more capital equipment. A second way to create additional capacity on capable machines is to increase the discipline with which those machines are operated. In the past, the full capabilities of individual processes or machines may not have been required to fabricate acceptable parts. Before purchasing new equipment, existing processes and machines should be analyzed for opportunities to increase both capability and capacity. The costs of obtaining additional capacity need to be considered carefully, especially if a redefinition of the precision assembly concept highlights opportunities for relaxing tolerance requirements.

*Fabrication and assembly.* Because detail parts are now in effect the assembly tools, the detail parts must be fabricated exactly as required by the precision assembly tolerances. The ability to compensate for detail part variation in the assembly tools is lost when the assembly tools are removed from the process. Any inaccuracies in the detail parts will lead directly to inaccuracies in the final assemblies. The burden of configuration control in the precision assembly factory therefore rests with the fabrication organization. The fabrication organization must be given the resources (time, money, and support personnel) required by this significant shift in responsibility.

Process documentation is an important means of attributing causes for failures in the fabrication and assembly arenas. Detailed process flow diagrams which document setup procedures, the order of machining steps, assembly sequences, etc. will prove invaluable in debugging a process which has produced unacceptable parts or assemblies. Figure 4.7 provides an example of an appropriate amount of detail in a process flow diagram. As the tolerances required by precision assembly represent such a dramatic change in the aerospace industry, problems in implementing precision assembly should not be unexpected. Thorough process documentation will be crucial in the effort to rapidly understand and correct processing deficiencies.



**Figure 4.7 Appropriate level of detail for process flow diagrams**

*Measurement and acceptance.* Perhaps the single biggest change in the aerospace industry caused by the introduction of precision assembly processes will be the way in which parts are measured and accepted. Today, the configuration of aerospace structures is controlled by the assembly tooling. Approximately once per year, the assembly tools are removed from service and verified by the quality assurance organization to be in the correct and legal (in accordance with Federal Aviation Administration regulations) configuration. These tool certification processes use complex measurement techniques (laser alignment systems, computer assisted theodolites, etc.) to certify large tools back to original engineering drawings, frequently with tolerance requirements in the  $\pm 0.030$  inches range. Accepting production structures can then be accomplished while the structures are still in the assembly tools by measuring gaps, edge margins, etc. between the structure and the certified tool. The measurement techniques required to check part-to-tool positioning are fairly quick and cost-effective, using tools as simple as feeler

gauges and micrometers. As long as the assembly tool is certified and has been used correctly, the structure will be acceptable.

Removing the assembly tools from the manufacturing process changes the importance of the measurement function dramatically. Today, the time required to certify a structure to an assembly tool is insignificant compared to the actual assembly time, due mainly to the simple measurement techniques required. Without the measurement baseline provided by the tools, accepting aerospace structures becomes a much more complicated process more akin to the tool certification processes described above. Because now the parts *are* the tools, the certification processes once used for tools on a *non-recurring* basis (perhaps yearly) must now be used on a *recurring* basis for every precision assembly structure built in the factory. Even worse, the time required to measure and accept a structure may be equal to or greater than the time required to assemble that same structure.

The potential for measurement processes to become a bottleneck in the precision assembly factory is very real. The measurement technologies currently used for tool certification may be accurate enough, but the time required to perform those measurements is prohibitive. The measurement processes which until this point were only used for tool certification will now be required to certify every precision assembly structure manufactured in the factory. As the number of structures to be measured increases, so does the burden of developing and documenting the appropriate measurement techniques for each different structure. Measurement processes which can rapidly and accurately verify parts and assemblies back to the original engineering data are required if assembly tools are to be removed from the factory.

*Summary.* As seen earlier in Figure 4.1, the end result of successfully implementing all three phases of the precision assembly methodology is a set of critical fabrication processes which are consistently capable of meeting the tolerances required by precision

assembly. The parts which are fabricated in those processes can then be assembled into aerospace structures without the use of complex and costly assembly tools. Thorough documentation of those critical processes is an important element which facilitates problem identification and solution generation. Once the preferred processes have been determined, statistical process control mechanisms should be used to measure, stabilize and improve the performance of the process around target values.

#### **4.4 Advantages provided by precision assembly**

Implementing precision assembly directly addresses three of the most important preferences placed by airline customers place on aerospace manufacturers: low price, superior quality, and reduced order lead times.

*Reductions in product cost.* The effects on product cost are probably the biggest advantage presented by precision assembly, yet they remain the most difficult to quantify. Precisely quantifying the effect of precision assembly on product cost was deemed to be beyond the scope of this research effort. But the following points can be made with reasonable certainty. The additional costs incurred during the more complicated fabrication stages should be more than offset by the dramatic reductions in expensive assembly tooling and costly, labor-intensive assembly processes. As fabrication begins to deliver higher quality parts, the opportunities for additional cost savings are clear: reductions in rework (and associated material and labor); reductions in expedited orders (and associated labor) as parts fit the first time; reductions in facility floor space requirements as assembly tools are dismantled, reductions in secondary planning efforts, dramatic reductions in the amount of paperwork required to document parts that do not fit and the corrective actions taken, etc. Additional cost advantages may be achieved as the flow of the product through the factory becomes quicker and more predictable, resulting



in less work-in-process inventory. In an industry where the customer is becoming more and more price sensitive, precision assembly is a way to satisfy this important customer need.

*Superior product quality.* Precision assembly processes will lead to increased product quality through the elimination of many of the variation-accommodating techniques used in the assembly world today. The shimming, grinding, and clamping done to detail parts and assemblies in today's manufacturing environment detracts from the appearance and performance of the final product. Customers are becoming increasingly reluctant to accept products which, although perfectly safe and reliable, have all the tell-tale scars and blemishes caused by being force-fit into the required configuration. The reduction or elimination of assembly shims through precision assembly techniques also makes the aircraft lighter, less susceptible to built-in stresses, and thus more desirable to the customer.

*Reduced cycle time leading to reduced order lead times.* Precision assembly processes are certainly not the point of highest leverage in the battle to reduce customer lead times. Because actual assembly time is only a small percentage of the total time required to produce an airplane, reducing assembly time through the application of precision assembly techniques will only have a minor effect on overall product cycle time. But as aerospace manufacturers work to reduce the non-value added time in their manufacturing processes, assembly time will become a larger portion of the cycle time, and reductions in assembly time will become more important in the long term. Today, however, precision assembly will only have a small effect on cycle time reduction.

The rationale for implementing precision assembly is not limited, however, to those advantages which are immediately tangible and can be passed on to the airline customer.

Precision assembly also provides aerospace manufacturers a number of strategic opportunities:

*Precision assembly will drive manufacturing to a position where it can become a source of sustainable competitive advantage.* The implementation methodology for precision assembly pictured in Figure 4.1 has one final important and as yet unmentioned detail. The diagram is drawn purposefully as a loop to indicate the potential long term payoff in affecting future product designs through the development of a new set of consistently capable manufacturing processes.

Linking the manufacturing organization with product designers during the design of a new product is nothing new; industry experience with concurrent engineering is well documented. The Boeing Company, for example, considers its experience with Design Build Teams (DBT) on the 777 program a success (Aviation Week and Space Technology 1994). But a manufacturing organization which has been challenged via precision assembly to develop and implement more capable processes will be able to provide input of a much higher quality to the design of future products. In this regard, the proactive development of manufacturing processes to meet the goals of precision assembly may very well open up new product design possibilities. Structures which until now have been designed with overly conservative edge margins, thicknesses, fastener counts, etc. because of perceived manufacturing shortcomings can now be optimized for competitive advantage.

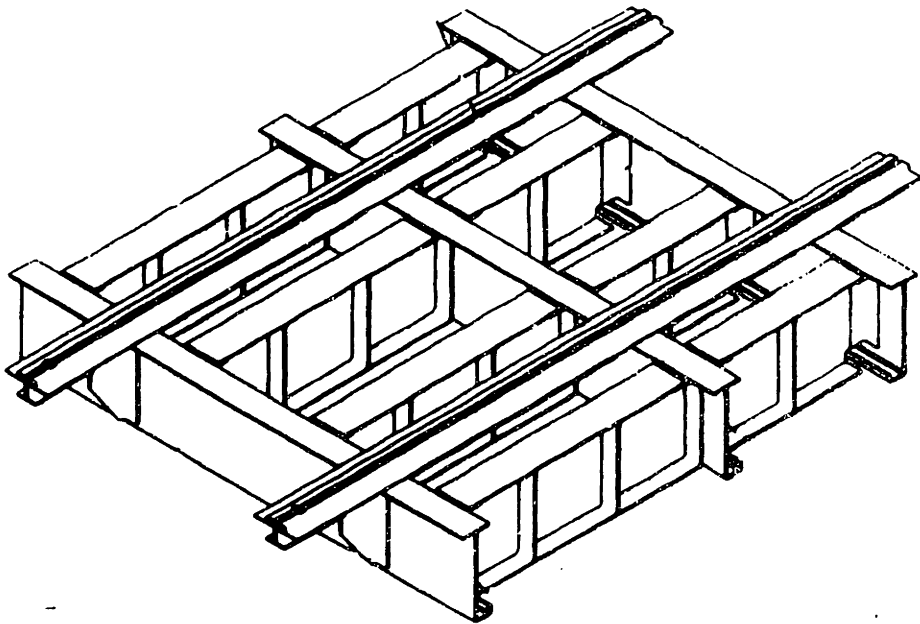
*Precision assembly provides focus for existing HVC efforts.* The vision of precision assembly and the elimination of assembly tools places extraordinary requirements on the fabrication organization, but also provides a real focus for process improvement efforts. As described in detail in Section 3, HVC efforts in the aerospace industry have failed to achieve their goals so far because the payoff to HVC in the current hand-fit, labor-

intensive assembly world is small. Precision assembly, on the other hand, *demand*s the accurate parts which effective HVC programs can help provide. The bottom line impact of effective HVC programs will be much clearer in the precision assembly factory.



## **Section 5. Case study: The precision assembly of an aircraft floor**

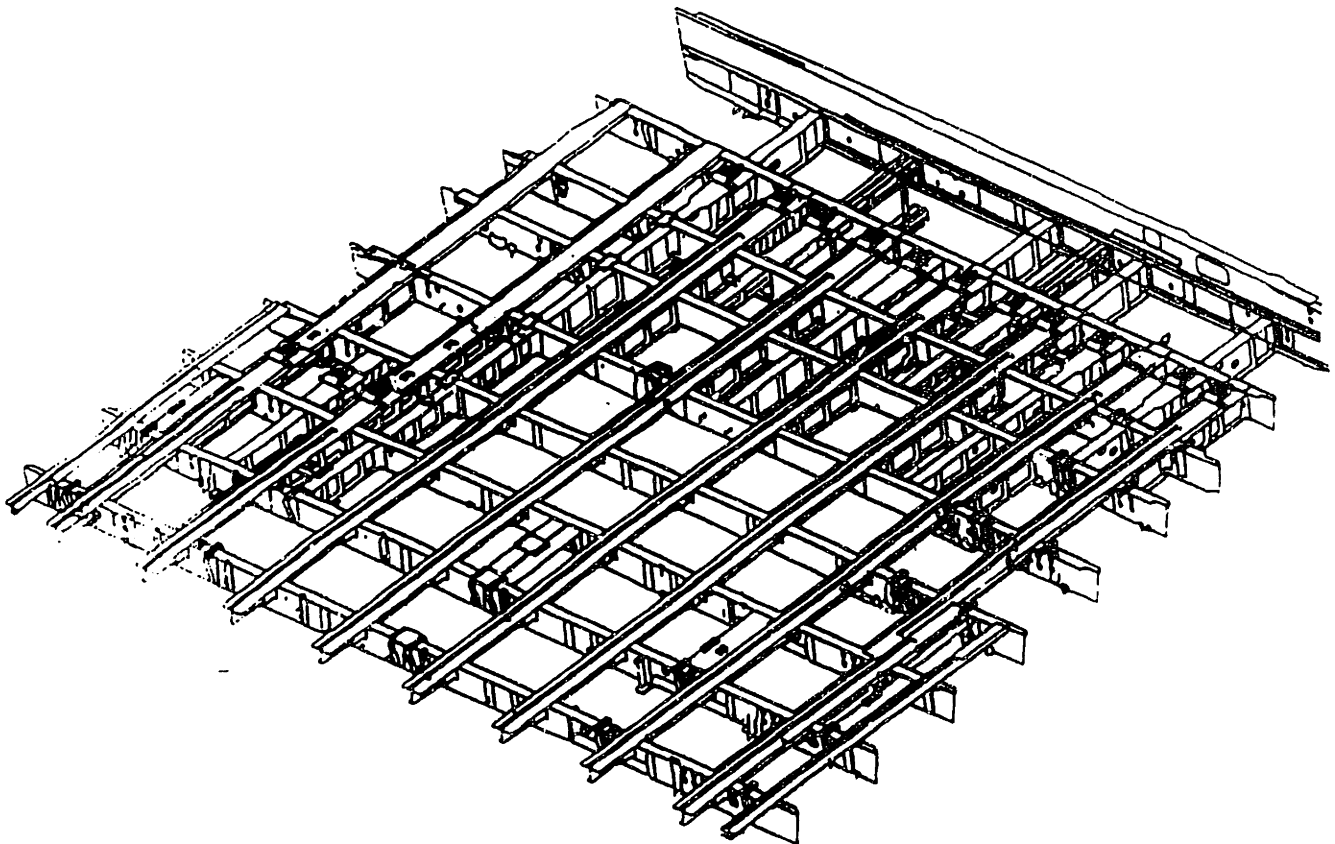
This section applies the methodology described in Section 4 to a typical aircraft floor structure. The structure pictured in Figure 5.1 is a subsection of an aircraft main floor. The majority of the research period was spent as a member of a cross-functional team responsible for developing the precision assembly methodology and applying it to this structure. This section will describe the entire three-phase process, from product design through the development and execution of the precision assembly concept. The research effort verified the feasibility of using precision assembly processes to build such structures without assembly tools. The decision to implement such techniques in the production of this floor has not yet been made.



**Figure 5.1 Floor grid structure for the precision assembly demonstration**

## 5.1 Phase I: Product definition

*Customer requirements and engineering design.* The complete floor structure pictured in Figure 5.2 was designed in an integrated product team (IPT) environment, where an internal cross-functional team was joined by customer representatives during the development of the product design. Customer requirements were well documented and customer representation on the design teams assured that their needs were addressed. All elements of the structure pictured in Figure 5.1 had complete 3D digital definitions, thus permitting the application of the proposed precision assembly methodology. The scope of the project was limited to the subsection of the structure pictured in Figure 5.1 in an effort to satisfy fiscal and time constraints while demonstrating the critical elements of the precision assembly concept as applied to an aircraft floor.



**Figure 5.2 Overall floor grid structure**

This all-aluminum structure is made up of 3 floor beams, 8 intercostals and associated clips, and 2 seat tracks and associated clips. The floor beams run transverse across the aircraft body and are located at different aircraft positions (distance in inches from a specified point, abbreviated as POS). Figure 5.1 shows the three floor beams to be located at POS 0, POS 16, and POS 38. All three floor beams are built from the same basic aluminum extrusion, but have small differences in their final configurations. In the finished aircraft, the ends of the floor beams are attached directly to the fuselage frames.

The intercostals and seat tracks are oriented perpendicular to the floor beams along an axis system termed the left or right hand of the aircraft. The center of the aircraft is defined as zero. The position of any structural component from the centerline is measured in inches and preceded by a right or left hand side designator (RHS or LHS). In the structure pictured in Figure 5.1, the intercostals are symmetrically located at LHS 16.5, LHS 5.5, RHS 5.5, and RHS 16.5. The four intercostals which connect the POS 0 and POS 16 floor beams are of the same design, as are those that connect the POS 16 and POS 38 beams. The seat tracks are located at LHS and RHS 11, and also have identical designs. Whereas the intercostals exist only for structural purposes, the seat tracks serve both a structural function and an important customer function: passenger seats (passenger aircraft) or cargo pallets (freighter aircraft) are attached to and can be moved along the seat tracks.

The structure is assembled almost entirely with Hi-Loks, a type of close tolerance threaded fastener often used in the aerospace industry for carrying high shear loads. Referring back to Figure 5.1, it can be seen that the intercostals have both an open and a closed end. The closed end of both sets of intercostals butts up against the floor beam at POS 16. A single set of Hi-Lok fasteners attaches both fore and aft intercostals at a given right or left hand side location to the POS 16 floor beam. At POS 0, four attach clips are used to secure the fore set of intercostals (those closest to the front of the aircraft) through their open end to the POS 0 floor beam. At POS 16 a similar set of four attach clips is

used to secure the aft set of intercostals, also through their open end, to the POS 38 floor beam. The seat tracks are attached to the structure with fasteners common to the caps of all three floor beams and with attach clips at the POS 38 floor beam.

*Key characteristics of the design.* The integrated product team which designed the main floor of the freighter derivative also identified its key characteristics. The key characteristics which apply directly to the subsection of the structure considered here are as follows:

- Floor beam ends positioned at correct locations (within +/- .030 in.)
- Floor flat (consecutive floor beam caps positioned +/- .030 in.)
- Seat tracks parallel (consecutive seat tracks positioned within +/- .030 in.)
- Seat tracks terminate at correct aft location (within +/- .030)

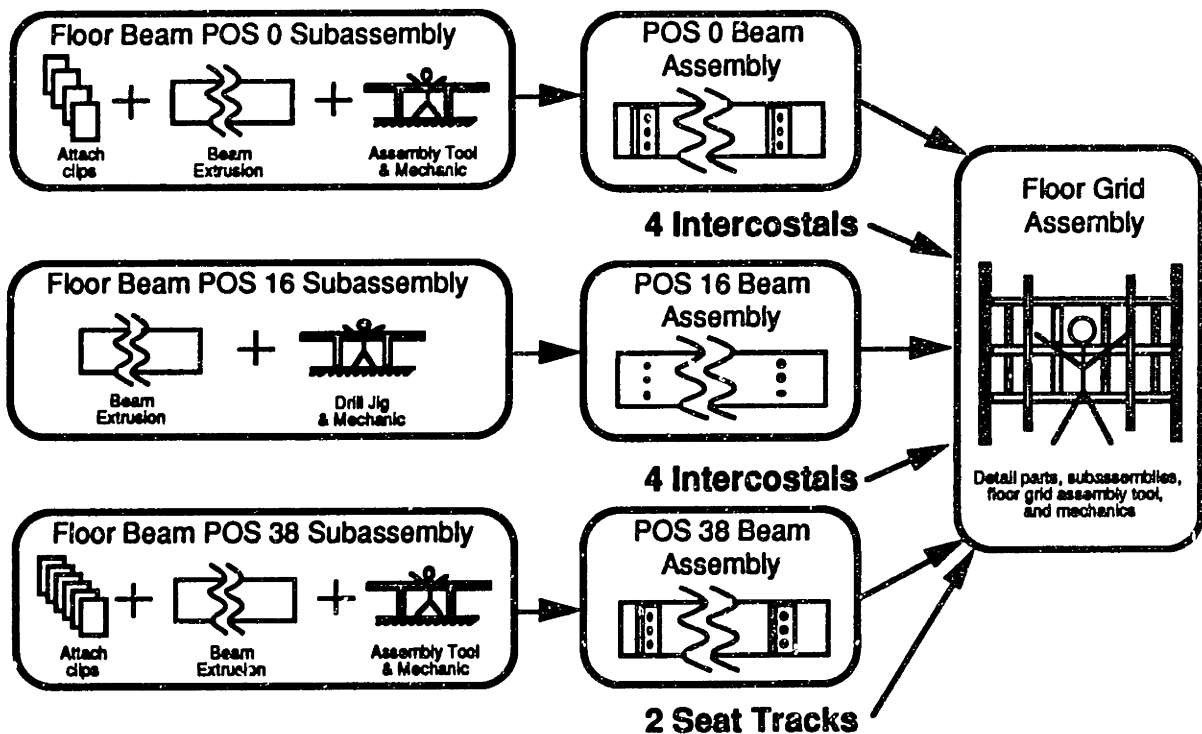
These key characteristics of the design will be used to focus the effort of developing a precision assembly concept for this structure in Phase II of the methodology. *Any* concept proposed must at a minimum meet these four design goals.

## **5.2 Phase II: Definition of the precision assembly concept**

*Precision assembly concept.* To understand the nuances of the precision assembly concept chosen for this structure, it is useful to first understand how this structure would typically be assembled. Figure 5.3 provides a description of the standard assembly processes for an aircraft floor. After fabrication of all the detail parts, the first task is to build the individual beam assemblies. In this case, the three floor beams each have their own dedicated beam assembly tool where all intercostal attach clips are fastened to the beams. In addition, any precision holes required in later stages of assembly are drilled using drill guides permanently attached to the beam assembly tool. The completed beam



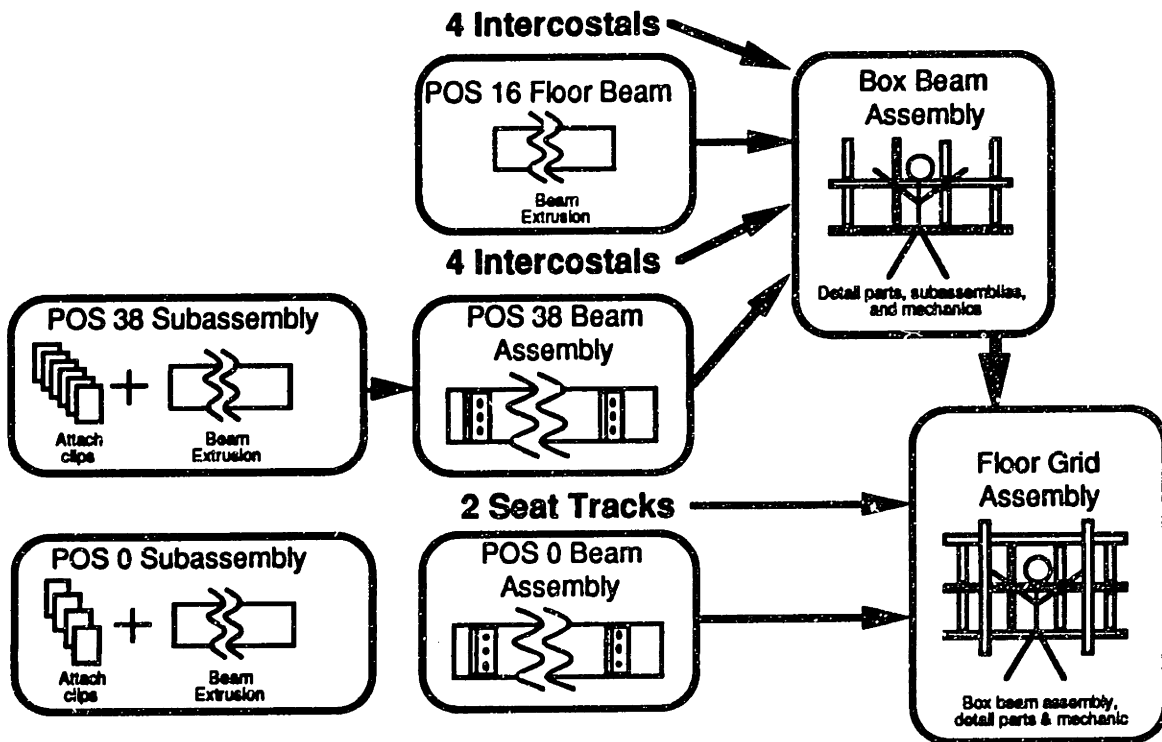
assemblies are next loaded into a large floor grid assembly tool against hard locating points. All intercostals and seat tracks are then loaded and located off of their own hard locating points. A skilled assembly mechanic follows by correcting any gaps or interferences between parts of the structure or between the structure and the tool. After the loading of the structure is complete, the mechanic begins the fastening process. Fastener holes are match-drilled between the parts of the structure, after which the parts are disassembled from the tool and deburred. Once deburring is finished, the parts are then reloaded and fasteners are installed. The assembly mechanic then repeats this fastening process on the next part of the structure.



**Figure 5.3 Typical assembly process for an aircraft floor (3 beam assembly tools and 1 floor grid assembly tool)**

The floor assembly process described above uses three beam assembly tools and one floor grid assembly tool. The labor expense of all the hand work performed by skilled assembly mechanics is a significant part of the product cost. But by using existing fabrication technology, this structure can be assembled without assembly tools. Specific fastener locations can be selected from the CAD digital data sets for each detail part and used as coordination holes from which one part can be located relative to another. Proper selection of these coordination holes will permit the fastening of detail parts to one another without the use of an assembly tool.

Figure 5.4 provides an overview of the precision assembly process proposed for this structure. Coordination holes in the floor beam extrusions and corresponding attach clips will permit the floor beam assemblies to be built without assembly tools. This step alone eliminates three beam assembly tools from the manufacturing process.



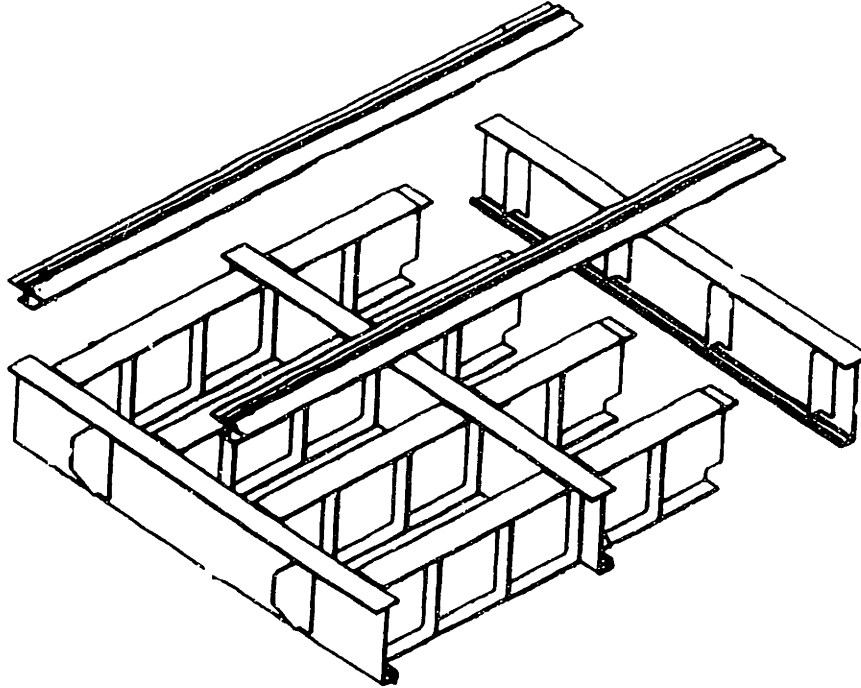
**Figure 5.4 Precision assembly process for an aircraft floor (No assembly tools)**

A goal of this demonstration project was to demonstrate two different ways of locating floor beams relative to one another. The first method uses the intercostals and attach clips to set the distance between two adjoining beams. This method is employed in the construction of the box beam assembly seen in Figure 5.4. The first step in the construction of the box beam assembly is to attach all eight intercostals to the POS 16 floor beam using four sets of coordination holes common to the POS 16 floor beam and the closed ends of the intercostals. Coordination holes in the free flange of the attach clips already fastened to the POS 38 floor beam assembly are then used to position the POS 38 floor beam assembly to the open end of the four intercostals already fastened to the POS 16 floor beam.

The second method uses the seat tracks to position two floor beams with respect to one another. This method is used to position the POS 0 floor beam relative to the box beam assembly. Coordination holes common to the seat track and the POS 0 and POS 38 beams are used to position the POS 0 beam relative to the entire box beam assembly. A 3D, exploded view of the structure taken directly from the CAD drawing file is provided in Figure 5.5. It shows how the seat tracks are used to position the POS 0 floor beam assembly to the box beam assembly. Because the positioning of the POS 0 beam is already completely determined, the fore intercostals can be fastened to the POS 0 attach clips using a standard match-drilling process. The assembly of the entire structure can thus be completed without using either the beam assembly tools or the main floor grid assembly tool.

The final element of the precision assembly concept was the choice of coordination hole size. A conservative approach would utilize undersized holes (typically 1/32 of an inch under the designed fastener hole size) to permit the reaming-out of slight mismatches in coordination hole positions discovered during the precision assembly process. The cross-functional team charged with developing this precision assembly concept decided to focus on the stretch objective of completing the assembly with full-

sized holes. The payoff to this approach is fairly large because it avoids the time-consuming task of disassembling, deburring, and reassembling the entire structure. It also avoids the rework caused by operator errors in the hand-drilling, reaming, disassembling, deburring, and reassembling of such structures today.



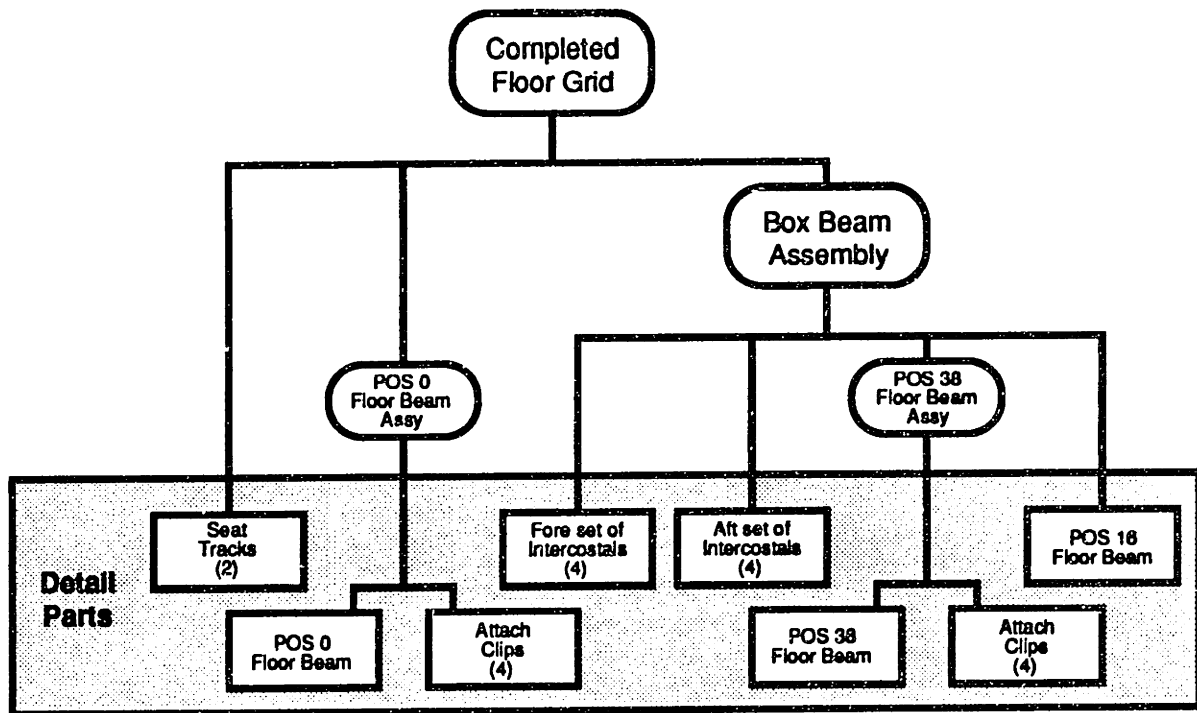
**Figure 5.5 Exploded view of the floor grid structure**

To eliminate the disassembly and deburr process, however, *all* fastener locations must be drilled in the detail part stage, as opposed to just a select few for coordination purposes. All fastener locations in the box beam assembly were drilled full-size in the detail stage to avoid match-drilling, disassembling and deburring such a complex structure. The team was required to take a slightly different approach in attaching the POS 0 floor beam to the box beam assembly via the seat tracks because of the match-drilling process required to join the fore set of intercostals to the POS 0 attach clips. In this case, only the minimum number of coordination holes required to accurately position the POS 0 beam were drilled full-size in the detail stage.

Note: The precision assembly concept described above was finalized only after much debate and analysis with statistical preassembly tools. In the interest of a logical presentation, many of the modifications made to the initial precision assembly concept were just incorporated in the concept description at this point. It is unlikely that a complete and accurate precision assembly concept could be developed without using the tolerance analysis or statistical preassembly tools to be described later.

*Precision assembly key characteristics.* Once the vision of the precision assembly concept was established, the design of the structure was analyzed for those attributes most critical to the success of the concept. Beginning from the completed floor grid assembly, a key characteristic tree was developed which flowed the key characteristics down through the box beam assembly into the individual detail parts. Figure 4.5 in the previous section shows the level of detail to which this process was carried for each floor beam subassembly. Figure 5.6 shows a top-level perspective of this flow down of key characteristics for all components of the floor grid structure.

*A computer model for performing statistical preassembly.* Once the precision assembly key characteristics have been identified, the next step in the methodology is to perform the tolerance analysis of the structure to specify the precision with which each of the detail parts must be manufactured. As described in Section 4, a key element of this process are statistical preassembly tools which permit the designer to easily simulate the assembly of the structure many times in the computer environment. In order to better understand the utility of statistical preassembly tools, the scope of this research effort was expanded to include the design and development of an in-house statistical preassembly



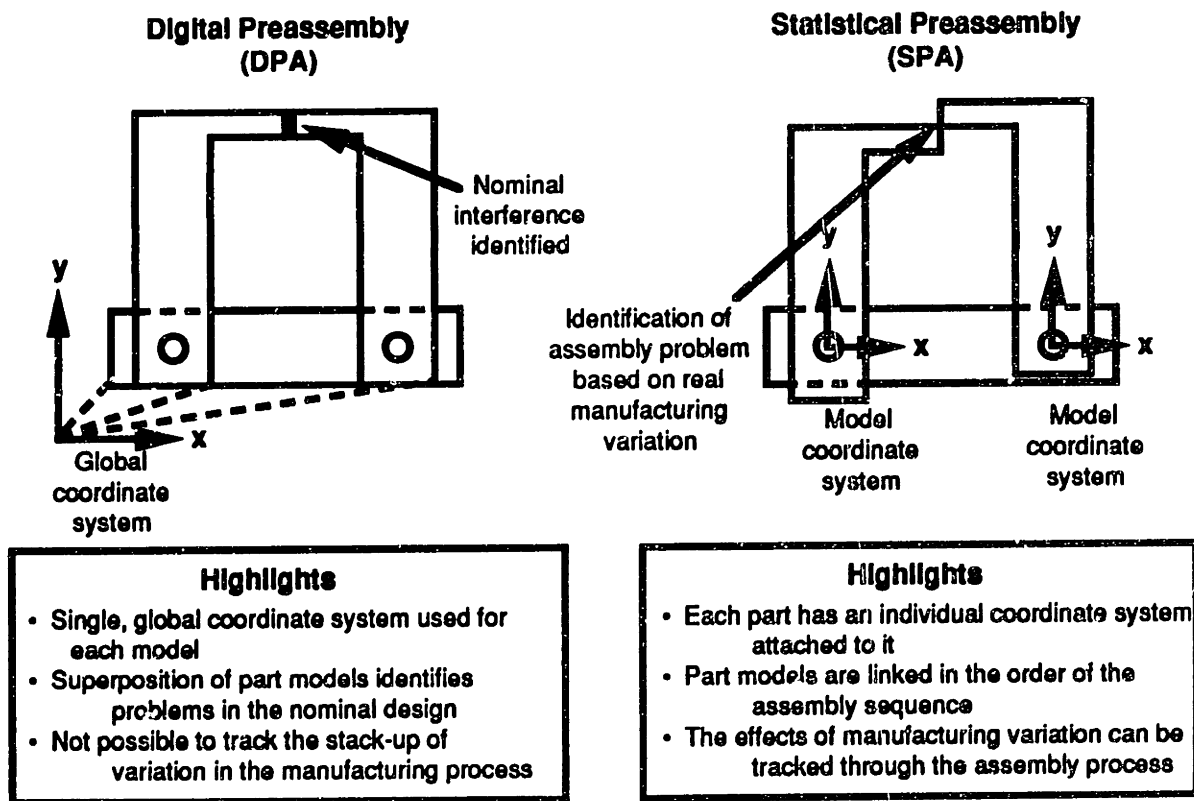
**Figure 5.6 Top-level flow down of key characteristics for the floor grid**

computer model. This model was then used to determine the tolerance specifications for all components of the box beam assembly.

The statistical preassembly model developed builds off of the variation-modeling work of Shalon (Shalon 1992). As part of his research into the effects of variation in the aerospace industry, Shalon developed a methodology he termed Indexed Pre-assembly with Variation (IPAV). The fundamental idea behind Shalon's and other statistical preassembly (SPA) tools is the use of both a conventional coordinate system and an index-point coordinate system (defined for each mating feature of a part) for all 3D digitally-defined parts. The index-point coordinate systems would permit the definition of a specific assembly sequence and allow for the modeling of part variations by adjusting the location of the index-point coordinate systems within the local model coordinate system of a part. The position of an assembled part in the global coordinate

system would therefore reflect the accumulated effects of variation of all previous parts used in the assembly.

Under perfectly nominal conditions, standard digital preassembly (DPA) tools and SPA tools like those described by Shalon would predict the same results. But because SPA models the effects of size, shape, and location variations and propagates them through the assemblies, it is capable of detecting interferences, misalignments and gaps due to a stack-up of variation in both parts and tools. DPA can only be used to check for interferences, misalignments and gaps in the nominal definition of a structure. Figure 5.7 provides a pictorial comparison of the difference in functionality between DPA and SPA analytical methods. The mathematical formulation used by Shalon and employed here is described in detail in Appendix A.



**Figure 5.7 Comparison of Digital Preassembly (DPA) and statistical Preassembly (SPA)**

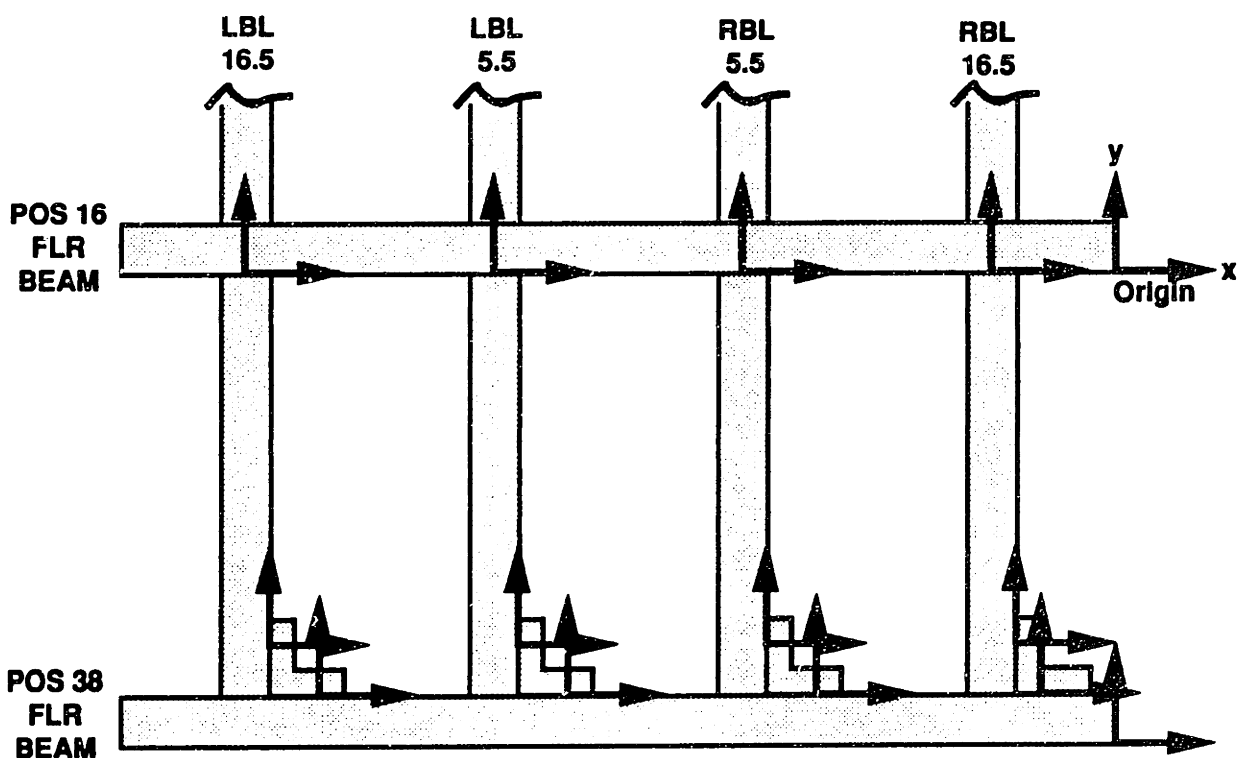
The formulation employed by Shalon had to be modified in three important ways prior to use in analyzing different precision assembly concepts. First, the IPAV methodology calls for the explicit modeling of all parts *and tools* in the assembly process. Precision assembly requires the elimination of assembly tools from the manufacturing process and they were therefore removed from the analytical formulation. Second, IPAV uses mating features of detail parts as the origins of his index-point coordinate systems. In the precision assembly world, the coordination holes used to locate parts relative to one another are used as the origins of the index-point coordinate systems. Third, and most important, the rapid analysis of many different potential tolerancing schemes was facilitated with the addition of a Monte Carlo simulation technique to the model. The inputs to the model are the  $\pm 3$  sigma manufacturing process capabilities for all design features which affect the assembly configuration (e.g., hole positions, part dimensions, etc.). The model will then probabilistically select from those normal distributions of process capability that iteration's "actual" values for those features and assemble the structure. Results from hundreds of such runs can then be compiled to better understand the impact of different tolerance specifications on the final assembly configuration.

*Applying the computer model to the floor grid.* Applying the statistical preassembly methods described above to the box beam assembly was fairly straightforward. The orthogonal nature of the structure and the absence of any complex-contoured parts made the development of the mathematical formulation relatively simple. The objective of this analysis was to identify those detail part tolerances required to satisfy the function of the assembly.

Figure 5.8 superimposes the index-point coordinate systems used in the analysis on a schematic of the box beam assembly. These coordinate systems will then be linked in the exact way in which the structure will be assembled, allowing for variations in the detail

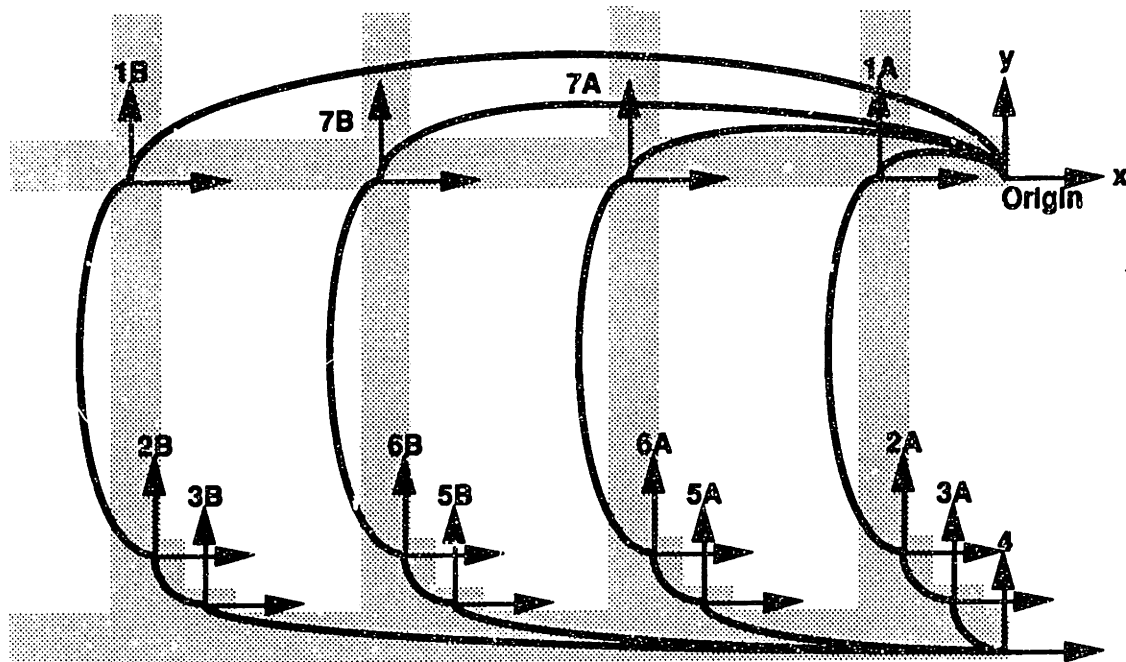


parts to be propagated through the assembly. The box beam assembly is assembled in a three step manner: first, all eight intercostals are fastened to the POS 16 floor beam. Second, the POS 38 floor beam is positioned relative to the POS 16 floor beam using only the two outermost intercostals and attach clips located at RHS and LHS 16.5. The final step is the fastening of the interior intercostals to the attach clips already attached to the POS 38 floor beam. Figure 5.9 removes the schematic of the box beam assembly to show this linking process in greater detail.



**Figure 5.8 Box beam assembly with individual part coordinate systems shown**

Appendix B provides a detailed description of the way in which the statistical preassembly model functions. In general terms, the analysis begins with the nominal positions (in 3 dimensions) of all coordination hole locations as specified in the design of each individual detail part. The user enters a set of geometric tolerance specifications



To determine distance from origin to 4: Origin to 1A, 1B to 2A, 2B to 3A, 3B to 4  
 To determine mismatch at Location 6: Compare Origin to 7A, 7B to 6A, 6B with 4 to 5A, 5B to 6A, 6B

**Figure 5.9 The linking of the individual part coordinate systems**

( $\pm 3$  sigma, normally distributed) which are then used by the model to turn all nominal coordination hole positions into "real" positions, simulating variability in the manufacturing process. These "real" positions are then used to generate the Euler angles required by the model to complete the transformation matrix (Appendix A). Each detail part model can then be linked in the order of assembly using the method described above, and the structure can be assembled hundreds of times to provide statistically significant results.

The model will simulate the assembly process of this structure to verify that assembly requirements are satisfied at two sets of locations. The first critical measurement sets are the three dimensional offsets between the RHS and LHS ends of the floor beams. This measurement will confirm that the beams ends terminate at the correct POS location and that the floor is being built in a flat manner. The second set of measurements to be

developed will be at the coordination hole interface between the webs of the interior intercostals and the attach clips pre-fastened to the POS 325 floor beam. The goal here is to tolerance the detail parts correctly to guarantee that fasteners can be inserted in the matching set of coordination holes found in both detail parts.

The inputs to be optimized are the tolerance specifications for those attributes of the detail parts which may affect the final configuration of the assembly. In this case there are four such specifications: the pattern and feature portions of the composite positional tolerances for each set of coordination holes (see Appendix C for a summary of composite positional tolerancing), the thickness tolerance for all detail parts, and the perpendicularity tolerance for all attach angles. In keeping with suggested ANSI practice (ANSI standard Y14.5M-1982), all input tolerances are specified using true position tolerancing as opposed to coordinate tolerancing methods. Four different levels of each input specification were used to evaluate the model: pattern tolerance (true position within .000, .0071, .0141, .0213 inches), feature tolerance (true position within .000, .0028, .0056, .0085 inches), web thickness tolerance (+/- .000, .002, .004, .006 inches), and perpendicularity tolerance (0, 0.5, 1, and 1.5 degrees). Assembly-level configuration requirements were used to determine the input specification ranges.

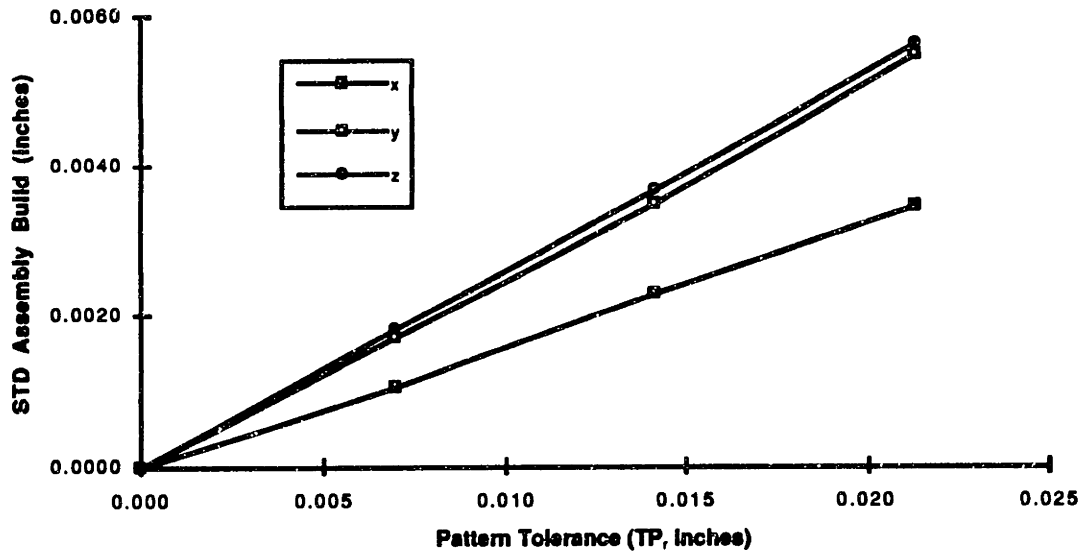
Because the effects of each tolerance specification on the assembly are completely independent, each can be analyzed separately to gain understanding of their effect on the assembly. Figure 5.10 shows the effect on the three-dimensional position of the POS 16 and POS 38 floor beam ends caused by varying each tolerance specification through its four levels. The standard design objective for this type of positional measurement is +/- .030 inches (+/-3 sigma) in all three dimensions, corresponding to a standard deviation (+/-1 sigma) of approximately +/- .010 inches. For the purposes of this demonstration, the design objective was narrowed to +/- .015 inches (+/-3 sigma). The horizontal axes in Figures 5.10(a) through 5.10(d) show the ranges over which the individual tolerance specifications for all detail parts in the assembly were varied. The vertical axes show the

effects on final assembly dimensions (measured in standard deviations) determined by building the assembly 500 times with the computer model.

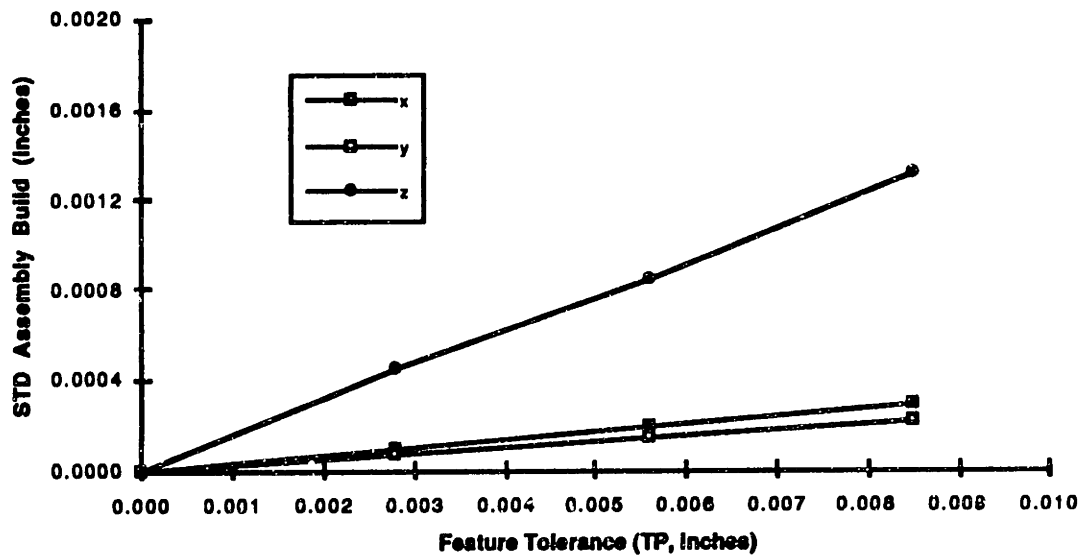
Figure 5.10(a) shows the effects on the final assembly of varying the pattern tolerance. In this case, 500 simulated builds on the computer shows that pattern tolerances of .007 inches (true position) result in a standard deviation of the assembly dimension of less than  $\pm .002$  inches in all three dimensions (x, y, and z). A  $\pm 3$  sigma value for the assembly can then be calculated ( $\pm .006$  inches), giving a high degree of confidence that parts made within such tolerance specifications will result in acceptable assemblies. Figure 5.10(b) shows that relaxing the feature tolerance specification through a reasonable range has little to no significant effect on the final assembly configuration. Even at a feature position tolerance as large as .0085 inches (true position), which is at the outer limit of the range over which a group of holes could still be expected to line up sufficiently to permit fastener insertion, the effect on the assembly is less than .001 inches ( $\pm 1$  sigma).

Figure 5.10(c) shows a very significant effect of changing the perpendicularity tolerance on the x-axis distance between the two ends of the floor beams. To meet the design objective, the perpendicularity tolerance must be set down near the  $\pm 0.3$  degree range, something very difficult to achieve on extruded aluminum parts. Reducing variability in the perpendicularity of the extruded parts is therefore a critical part of this precision assembly concept. Figure 5.10(d) shows a small effect on the positions of the beam ends by varying the web thickness tolerance. Varying the web thickness of the floor beam extrusions has no effect on the measurements in the y and z axes, as would be expected.

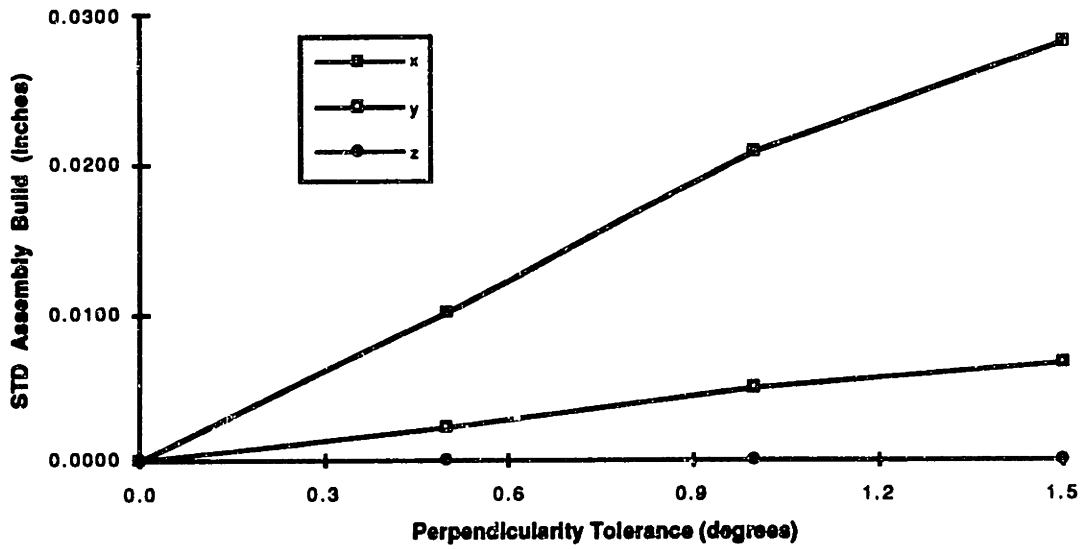
The primary application for such statistical preassembly tools is to better understand the effect of variation in detail parts on the assembly-level function of the design. Statistical preassembly tools should be used with caution, however. The limitations noted earlier in Section 4.2 are very real. Tools which cannot accurately model flexible



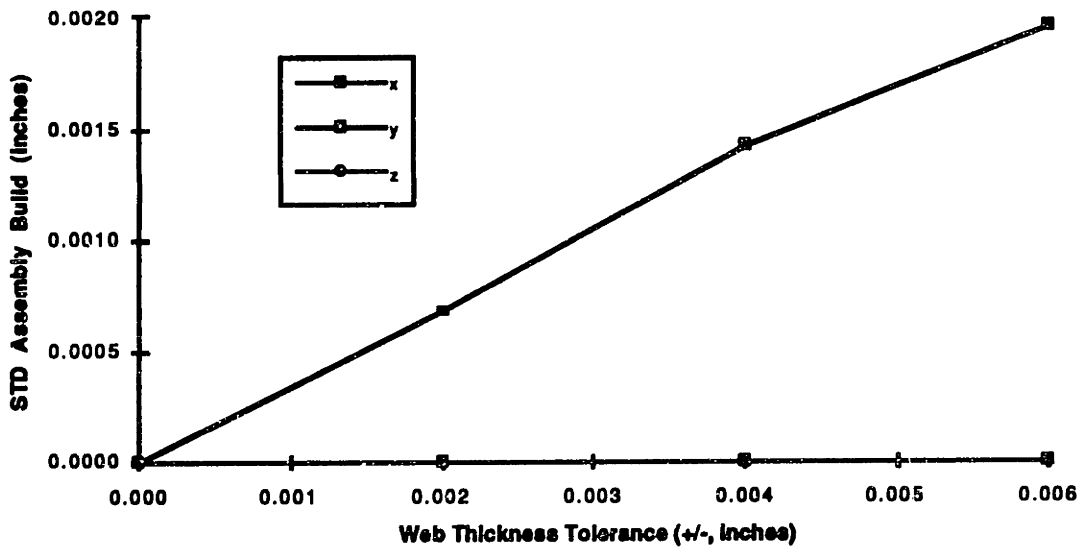
**Figure 5.10(a) The predicted effects of different pattern tolerances on the final assembly configuration**



**Figure 5.10(b) The predicted effects of different feature tolerances on the final assembly configuration**



**Figure 5.10(c) The predicted effects of different perpendicularity tolerances on the final assembly configuration**



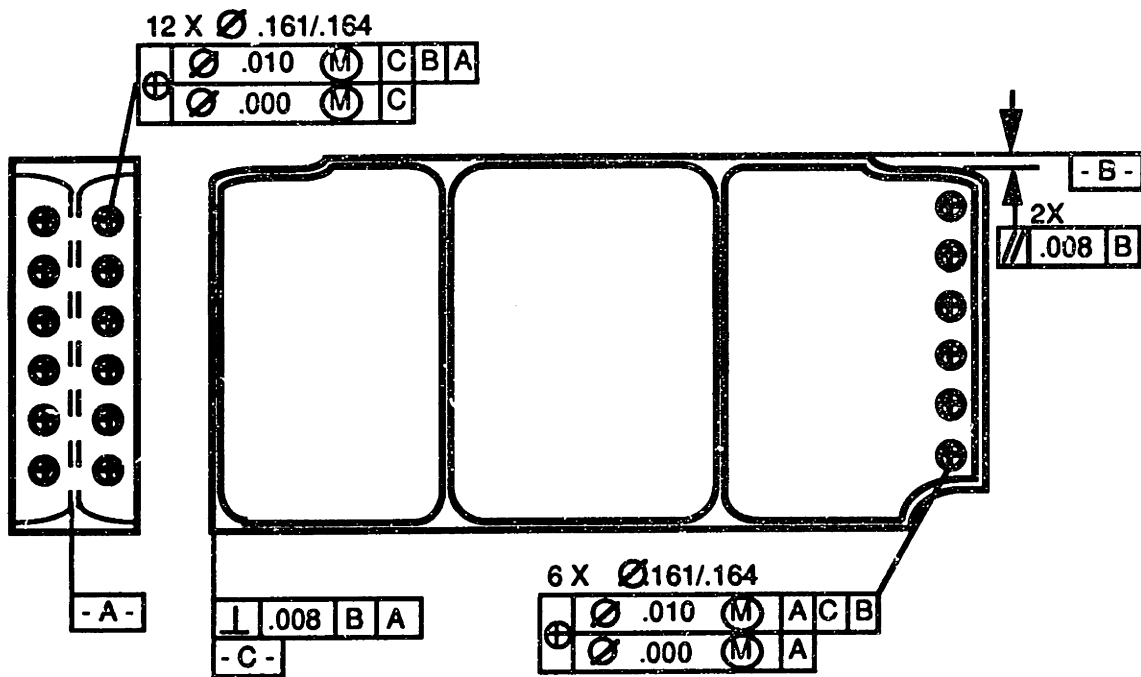
**Figure 5.10(d) The predicted effects of different web thickness tolerances on the final assembly configuration**

structures or compliance during the assembly process have inherent limitations: they may incorrectly predict that a structure will not assemble in the desired configuration. The model developed as part of this research effort was invaluable in understanding counter-intuitive variability effects on different elements of the design. However, the results it produced were typically very conservative and, if applied without judgment, could drive the manufacturing organization to excessively accurate and expensive processes.

*Geometric dimensioning and tolerancing of the engineering drawing.* After completing the computer analysis of the different possible tolerance specifications, the designer uses that analysis as a basis for assigning tolerances to the different components of the assembly. These tolerance specifications should be included directly as part of the CAD solid model of the individual detail part. The fabrication organization will use both the solid model and the tolerance specifications to select manufacturing processes, fabricate the parts, and perform all measurement and acceptance tasks.

Figure 5.11 shows how the tolerances on the aft set of intercostals were eventually specified. Note the use of composite positional tolerancing in the specification of the coordination hole positions. Also note the feature tolerance of a true position within .000 inches. The concept of bonus tolerance defined in Appendix C (any bonus tolerance not used in the diameter of the hole may be applied to the positional tolerance) is of critical importance here. In the case of the intercostals, if the hole diameters can be maintained at .164 inches (.003 more than the specified minimum of .161 inches), the feature positional tolerance obtains a "bonus" of .003 inches. All floor beams, intercostals, attach clips and seat tracks were toleranced in a similar fashion.

*Summary.* Phase II begins with the development of the precision assembly concept and its key characteristics. Once both are well in hand, statistical preassembly tools can



**Figure 5.11 Geometric dimensioning and tolerancing of the intercostal drawing**

be employed to assist the designer in the tolerance engineering process. The designer can rapidly iterate through different tolerance specifications to derive the tolerances which will provide the highest probability of precision assembly success while maintaining fabrication requirements at reasonable and cost-effective levels.

### 5.3 Phase III: Execution of the precision assembly concept

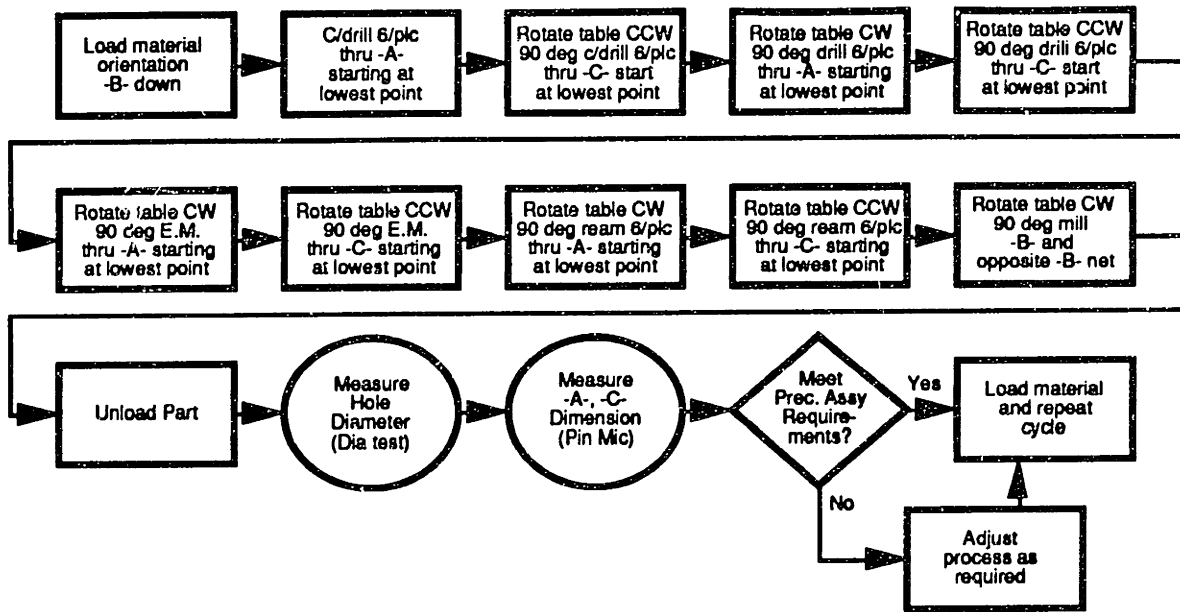
*Selecting the appropriate manufacturing process.* Once the tolerance specifications have been documented and provided to the fabrication organization, manufacturing processes must be selected to fabricate the detail parts. Because the tolerances required of precision assembly parts will be tighter than similar non-precision parts, great care must be taken in the fabrication organization to draw a distinction between parts destined for precision versus standard assembly processes. Manufacturing engineers responsible



for planning the part routings through the factory must be cognizant of this distinction and make a concerted effort to work with the fabrication organization in identifying appropriate and capable processes. Machines which have always been used to fabricate a specific set of parts may not be accurate enough to satisfy the requirements of precision assembly. A more likely scenario, however, is that completely capable machines are being operated in a less than ideal manner simply because the full capability of those machines has never been required to produce acceptable parts.

In the specific case of the floor grid, much of the demonstration hardware was fabricated on machines typically considered less capable than those machines actually specified for full-scale production. The tighter tolerances were achieved on supposedly inferior machines by paying close attention to all elements of the fabrication process. The difference between machine capability and process capability is significant. The experience in fabricating the floor grid components demonstrated clearly that the manner in which a piece of equipment is operated (setup, calibration, proper feeds and speeds, etc.) is often far more important than the raw specifications on the accuracy of the machine. The lesson is that selecting the appropriate manufacturing process for precision assembly parts involves much more than verifying machine capability; even the most capable machine operated in poor fashion will fail to satisfy the requirements of precision assembly.

*Fabrication and measurement.* After the selection of the manufacturing process, the 3D digital data is converted to the required machine language and down-loaded directly to the fabrication machine. The importance of documenting all steps of the fabrication process cannot be overstated. Accurate process flow diagrams are an invaluable source of information when trying to debug a fabrication process which has produced unsatisfactory detail parts. Figure 5.12(a) documents the process used to fabricate the



**Figure 5.12(a) Example: a machining process prior to revision**

first attach clips on a standard mill retrofitted with a rotary table for single setup, multi-axis work. The process produced parts whose hole patterns on two different faces were offset by a constant and unacceptable amount. In analyzing the process, it was noticed that process capability could be improved by reducing the number of part rotations and inserting a simple y axis deviation check (and offset load if required) as shown in Figure 5.12(b). All parts produced on that machine from that point on were acceptable.

Verifying that the detail parts satisfy precision assembly requirements is a fundamentally new task for quality assurance organizations in the aerospace industry. The increase in the number of parts with very tight tolerances will place a premium on measurement processes which can quickly and accurately verify part configuration. Simple components like attach angles which were previously checked visually against mylar drawings must now be measured with precision height gauges or coordinate measurement machines. The measurement function then becomes even more important because unacceptable parts which are reworked or scrapped in the detail stage will be

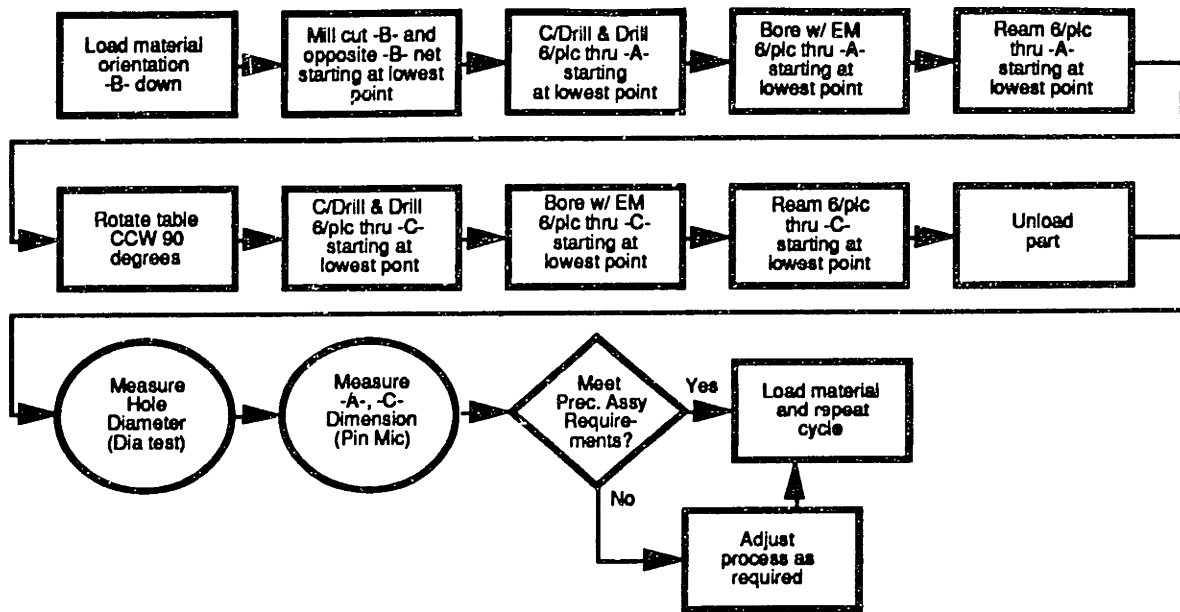


Figure 5.12(b) Example: the same machining process after revision

assembled into structures which do not meet assembly requirements. At that point, of course, attributing causes for the assembly problems becomes much more difficult because of the number of parts involved. The percentage of time required for measurement processes therefore grows substantially with the addition of the precision assembly tolerances, from insignificant levels to magnitudes equal perhaps to the fabrication time itself.

*Assembly and measurement.* The floor grid structure assembled quickly and accurately. The assembly was performed by production mechanics familiar with the assembly of similar structures with standard techniques and tools. All involved in the precision assembly process were impressed at the ease of assembly, particularly in light of the use of all full-sized holes. The force required to insert the Hi-Lok fasteners in the pre-drilled holes was no more than typical requirements. Total time to assemble the

structure pictured in Figure 5.1 was less than thirty minutes, a dramatic improvement over existing assembly processes.

Verifying that the structure was in the correct configuration was a more complicated task, however. Measurement technicians experienced difficulty in correctly orienting the structure in relation to the coordinate measurement machine (CMM). These orientation problems limited the ability of the measurement technicians to accurately define the primary measurement axes of the structure and hence made accurate measurement of the structure very difficult. The experience highlighted the problems inherent in measuring relatively large and complex structures in free space. The inability to measure structures in relation to a certified assembly tool of known dimensions thus complicates the measurement and acceptance of aerospace assemblies. After developing a more robust coordination scheme, technicians were able to measure and verify the structure to be in the proper configuration. All key measurements were within .015 inches of the nominal design parameters.

#### **5.4 Final observations from the case study**

The top-level documentation of the precision assembly process, including the detailed description of the application of the methodology to an aerospace structure, is now complete. The decision must now be made whether to implement the precision assembly methodology on a wider scale. A number of key observations made during the six-month effort to develop and implement the precision assembly concept may help focus the discussion of widespread implementation.

- The implementation of precision assembly techniques will drive the development of more capable fabrication processes. It remains to be seen whether future Integrated Product Teams will be able to leverage those improved manufacturing capabilities in the

development of superior product designs, providing a competitive advantage in the marketplace.

- **Process capability, and not machine capability, is the key to precision assembly. In most cases, increased process discipline in the factory will satisfy any precision assembly requirements and avoid expensive and unnecessary investments in capital equipment.**

- **Measurement processes will become a bottleneck in the precision assembly factory. The development of faster and more accurate measurement processes, especially for larger and more complex structures, is a point of high leverage in efforts to implement precision assembly.**

- **The existence of 3D digital definitions for all detail parts and for the assembled structure is absolutely essential. Precision assembly should not be attempted without it. The cross-functional team spent one fruitless month investigating precision assembly concepts for a pre-CAD defined floor structure before abandoning the effort.**

- **Statistical preassembly techniques are an invaluable tool in gaining a deeper understanding of the effect of detail part variation on the final configuration of aerospace structures. They provide the designer with additional analytical capabilities to increase the accuracy with which tolerances are assigned to the components of a design. Eventually these analytical capabilities can be used to generate a set of design rules to codify precision assembly requirements and permit them to be included in the design of future products. However, such tools have inherent limitations (inability to model flexible structures, inability to model the effects of compliance during the assembly process, etc.).**

- **Geometric dimensioning and tolerancing should be used in the development of precision assembly concepts. Standard coordinate tolerancing methods communicate less of the designer's true intent and are more restrictive than geometric tolerancing methods. Manufacturing personnel need to be trained in the nuances of geometric dimensioning and tolerancing, including the concepts of bonus tolerances and composite positional**

tolerancing. The misapplication of GD&T in the design or manufacturing process, however, can have significant negative impacts on the factory -- either through poorly developed or executed precision assembly concepts.

- This research effort demonstrated the technical feasibility of precision assembly. The financial desirability is another matter, however. Although the savings in assembly cost and time, in reduced tooling requirements, and in reduced rework are certainly compelling, the increases in fabrication cost are also significant. Accurately predicting the true financial impact of precision assembly may be impossible, especially if many of the postulated cost savings from reduced hardware variability are realized. The strong desire to quantify the financial effects cannot erase the fact that any financial analysis will be extremely sensitive to the many arbitrary assumptions required to perform such an analysis. The results of any analysis of the financial impact of implementing precision assembly will therefore be suspect.

## **Section 6. Organizational barriers to implementing precision assembly**

The precision assembly methodology proposed in Section 4 represents a dramatic change in the process technology of aircraft manufacturing. But while the technological implications of precision assembly will be significant, the organizational ramifications may be even more far-reaching. In fact, the advantages achieved by the use of precision assembly processes may be *unrealizable* without significant changes in organizational structures and policies. In this section, I argue that the successful transition of the precision assembly methodology into the factory environment will depend on the ability of management to lead large-scale, difficult change efforts in *both* the technological and social systems within the factory.

Two major reasons exist for why the implementation of precision assembly will require large-scale organizational change. First, there exists a fundamental lack of fit between the cross-functional requirements of precision assembly and the existing functional organization. The precision assembly methodology requires an organizational system which does far more than permit or encourage cross-functional communication and learning. Indeed, the cross-functional transfer of knowledge must be *designed* into the precision assembly organization. The obvious inefficiencies associated with the implementation of such a cross-functional process within a functional environment (for example, inefficiencies in time, cost, and the quality of information transfer) can only be addressed through a fundamental redesign of the organization. More importantly, deeper levels of process knowledge (i.e., understanding exactly what process inputs will result in acceptable outcomes) are best acquired in cross-functional environments where all parameters affecting process outcomes are under the control of a single organization.

Second, the initial process of implementation must not be focused only on the short-term goal of assembling a particular aerospace structure without tools. The focus instead should be on the development of an organization with the capability of using the

methodology to efficiently assemble *any* structure without tools. Rather than emphasize the rigid adherence to the proposed methodology, management should strive to foster a never-ending process of experimentation with and continuous improvement to the process of precision assembly. Once these two goals have been accepted as the basis for implementation, it becomes clear that the biggest barriers to achieving such long-term capabilities are organizational (and not technological) in nature.

This section will analyze a typical aerospace organization and identify structures, procedures, and policies which are likely to be affected by the implementation of the proposed precision assembly methodology. Section 6.1 begins with a detailed description of the existing organization. In Section 6.2, I explain why I think it is essential to pay equal attention to managing the organizational change process caused by the introduction of new manufacturing technologies. Section 6.3 focuses on a set of top-level barriers (organizational, political, and cultural) which will tend to oppose the implementation of precision assembly in a general sense. Section 6.4 analyzes the specific misalignments between the proposed methodology and the existing organization. I provide a set of recommendations for overcoming the organizational barriers to precision assembly in Section 7, along with a discussion of the implementation process.

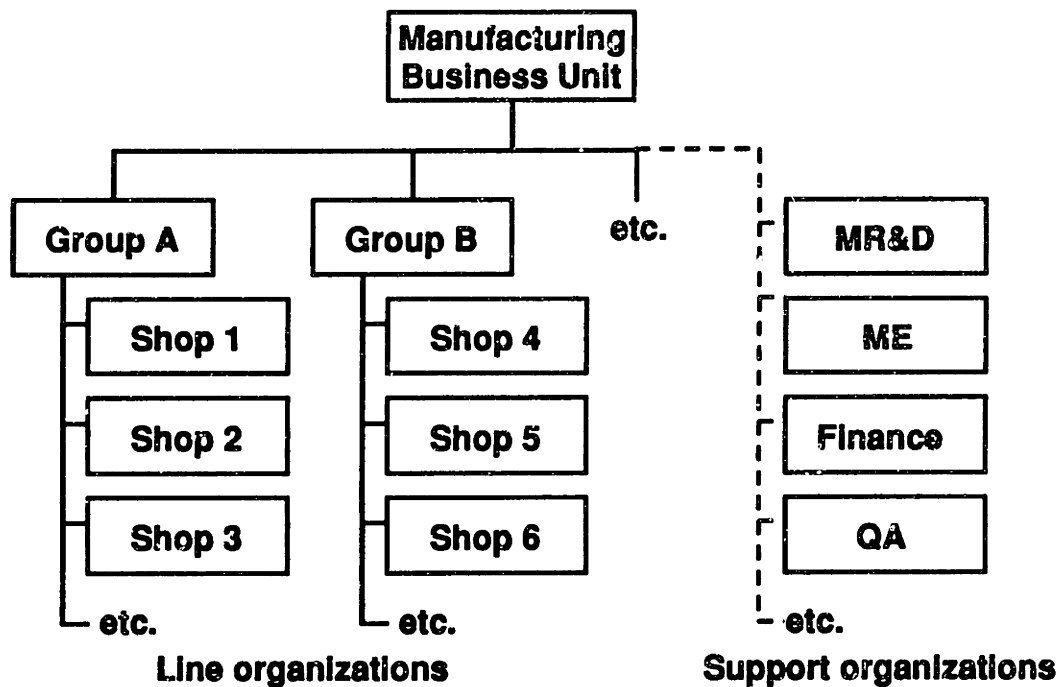
## **6.1 Organizational Background**

The aerospace organization where the research was performed manufactures large sections of many different passenger aircraft models. It produces everything from small subassemblies to complete aircraft fuselage sections. The balance of the business base is comprised of engine struts and nacelles, aircraft doors, flight control surfaces, and various other aircraft subassemblies.

The Operations organization is divided into four Manufacturing Business Units: Fabrication, Subassembly (small assemblies), Assembly (major assemblies), and Engines.



A Manufacturing Business Unit (MBU) is a cross-functional organization made up of all direct and support organizations required to design and manufacture a particular segment of the business. The core members of the MBU are the factory workers and supervisors; support organizations like Manufacturing Research and Development (MR&D) and Manufacturing Engineering (ME) are matrixed into each MBU on a dotted-line basis. Figure 6.1 provides a representation of the organizational structure. Wherever possible, all functions within a MBU are co-located.

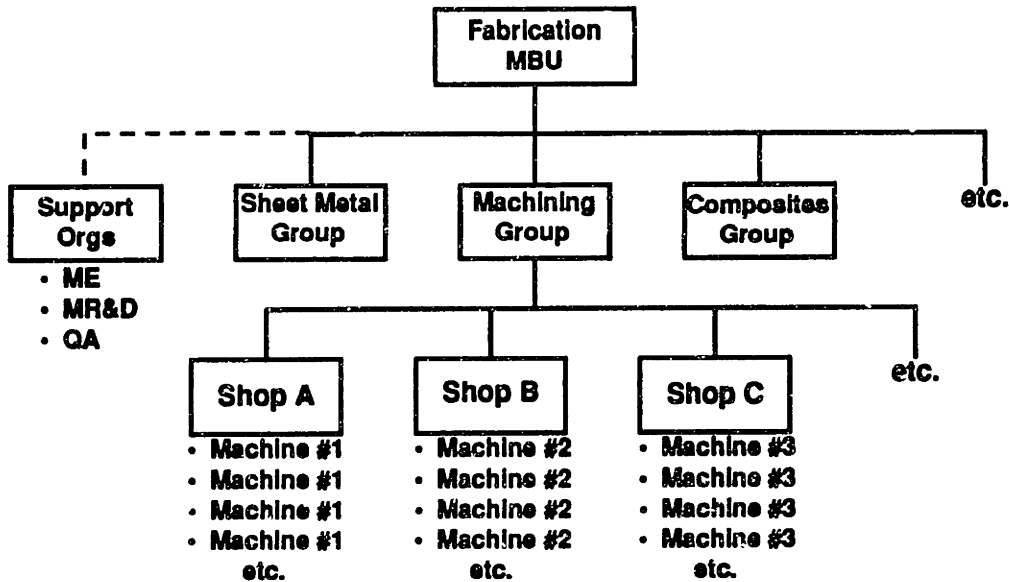


**Figure 6.1 Representation of the Manufacturing business Unit (MBU) organizational structure**

*Fabrication organization*

Figure 6.2 provides a pictorial representation of the existing Fabrication Manufacturing Business Unit (Fab MBU) organization. The organization is divided into major groups (machining, sheet metal, composites, etc.), which are then further divided

into individual shops. Fabrication of detail parts is typically done in batches, with similar machines located next to one another.



**Note: Organization based on PROCESS**

**Figure 6.2 Representation of the existing Fabrication MBU**

For planning purposes, all machine groups within the factory are assigned control codes. The control-code flow time is the length of time that a particular part will remain in a specific control code before moving to the next control code in the processing sequence. This flow time includes not only direct machining time, but also any upstream or downstream idle time within the control code. The control code flow time is set conservatively to protect final scheduled delivery dates, resulting in buffers of both time and material between sequential control codes. Such buffers tend to restrict the flow of information between sequential control codes.

Typical metrics like labor efficiency and machine utilization are calculated and used to manage the flow of material through the fabrication organization. The use of labor efficiency (standard labor hours divided by actual labor hours) is justified as a measure of

labor effort and effective scheduling. Machine utilization (hours run divided by total hours of machine availability) is presumed to measure effective scheduling and machine choice, and is often used to justify capital equipment purchases. Individual shops are given very clear incentives to maximize labor efficiency and machine utilization, but efforts at increasing quality and reducing variability are not so clearly rewarded.

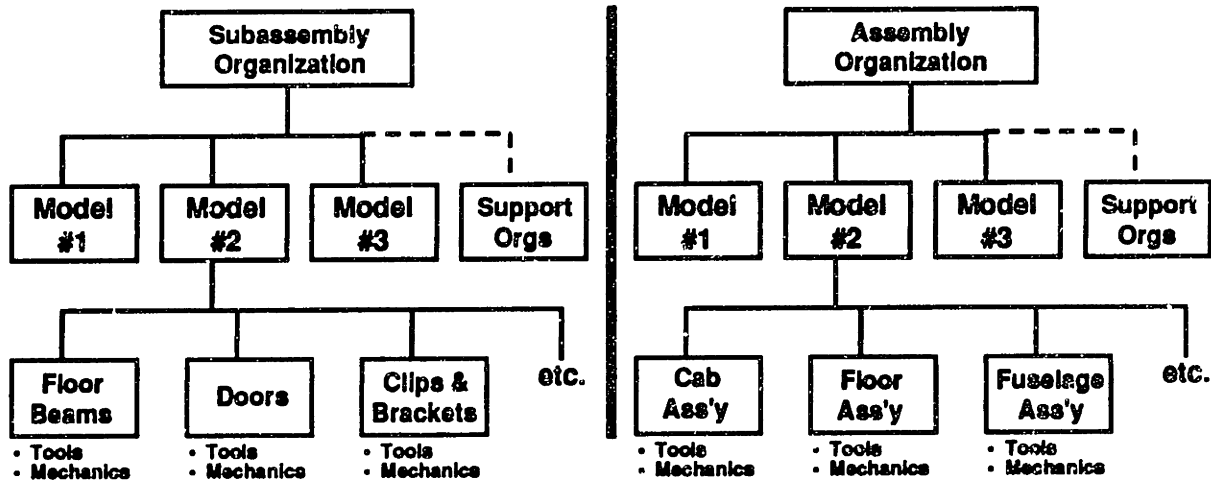
Support organizations like Manufacturing Engineering (ME) and Manufacturing Research and Development (MR&D) are “soft-lined” or matrixed into the Fab MBU. Although all support organizations are co-located with the Fab MBU, they maintain direct hierarchical ties back to their functional organizations. Maintaining functional centers of expertise is considered important because organizations need a place where functional learning can be collected, synthesized, and transmitted to the other parts of the organization (Womack and Jones 1994).

The desire to maintain functional depth, however, presents a number of challenges for an organization striving for true cross-functional interaction. Functional specialists often feel a stronger commitment to their function and its intellectual tradition than they do to cross-functional teams because of the required depth of knowledge and the time and effort needed to acquire their functional knowledge (Womack and Jones 1994). Perhaps one reason for the limited success of cross-functional teams within the Fab MBU is that team leaders are given all the responsibility of leading cross-functional efforts, but none of the authority necessary to make things happen. Team members continue to be evaluated and promoted from within their own functional organizations. This rigid adherence to functional definitions tends to limit the communication within the team and unnecessarily complicates the command and control of cross-functional teams.

### *Assembly organization*

Figure 6.3 is a representation of the two organizations performing assembly tasks: the Subassembly and Assembly MBUs. The Subassembly MBU is responsible for the

assembly of small structures whereas the Assembly MBU performs the major assembly tasks in the factory. Each MBU has its own leadership team, work force, and matrixed support organizations. As with the Fab MBU described above, the Subassembly and Assembly MBUs have found it difficult to establish effective, permanent lines of cross-functional communication within the existing matrixed structure.



**Note: Parallel organizations based on product line**

**Figure 6.3 Representation of the existing, parallel Subassembly and Assembly MBUs**

The use of control codes is also prevalent in the assembly organization. Industrial engineers estimate the number of labor hours required to perform each separate assembly task, and set a conservative control code flow time based on that estimate. Requirements for assembly tool positions are determined by the relationship between the flow time through each control code and the required aircraft delivery rate (e.g., a control code with a flow time of eight days and a target aircraft delivery every four days would require two assembly positions). As all of the configuration-controlling information resides in the assembly tools permanently positioned at each control code, very little communication takes place (or needs to take place) between sequential control codes.

## **6.2 The importance of managing the organizational changes associated with technological innovations**

If organizations are to use new process technologies as a means of increasing manufacturing productivity, management must take a leadership role in identifying those aspects of the organization's structure, culture, and operations which must be changed to facilitate the use of these new technologies. The interdependence within organizations of task, structure, people, and technology means that the introduction of new process technologies is not a simple one-dimensional problem (Leavitt 1964). The implementation of the precision assembly process is designed to improve the manufacture of aircraft structures, but will certainly precipitate change in organizational members and structures as well.

### ***Implementing precision assembly will require organizational change***

*New manufacturing technologies almost never fit perfectly into the user environment.* After studying the introduction of new process technologies in a number of different industries, Leonard-Barton has concluded that technology transfer requires a continuous, ongoing dedication to the process of change. The conscious management of mutual adaptation between the technology and the host organization is required because the technology will never exactly fit into the user environment (Leonard-Barton 1988). The precision assembly methodology proposed in Section 4 is sufficiently different from today's aerospace manufacturing processes that its introduction into the existing organization will require some degree of organizational adaptation. For example, the segmented, functional design of today's manufacturing organization is well-suited for a manufacturing process which requires little to no horizontal communication between functions to produce acceptable structures. The very cross-functional nature of precision

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assembly, however, will highlight the absence of such inter-process communication mechanisms and compel changes in structure and responsibilities.

*The interaction of new manufacturing processes like precision assembly with the organization is not readily predictable.* The choice of one implementation strategy over another depends heavily on the novelty of the manufacturing process and the experience the organization has had in adopting similar processes. Although the manufacturing organization is constantly introducing new process technologies in an effort to remain competitive, the organization has relatively little experience with such large scale changes in the process of fabricating and assembling aircraft. In fact, the aircraft assembly process used throughout the aerospace industry has remained essentially unchanged for the past fifty years. In the case of precision assembly, the novelty of the methodology within the aerospace industry will require more adaptive organizational designs than currently extant in order to compensate for unanticipated difficulties during implementation. Thomas' (1994) conclusion that people will use the implementation of new process technologies as a mechanism through which to alter not only the performance of work but also their status, influence and self-concept is particularly relevant here. In an effort to redefine their position within the firm, those responsible for the implementation of precision assembly will alter both the nature of the technology and the structure of the organization in ways which simply cannot be predicted with any degree of certainty.

***Organizational forces will oppose precision assembly and hinder its implementation***

In the implementation of new process technology, the importance of individual acceptance of the new technology is often cited as a prerequisite for successful introduction and use (Liker and Fleischer 1993; Liker, Roitman, and Roskies 1987; Leonard-Barton 1988). In other words, unless individuals within the organization view

the net effect of the new technology on them and their career prospects as positive, they are likely to resist the introduction of the new technology in an effort to maintain the status quo. Other possible sources of resistance to change include: the proposed change ignores the needs, attitudes, and beliefs of organizational members; individuals lack specific information about the change; individuals do not perceive a need for change; organizational members have a “we-they” attitude which causes them to view the change agent as the enemy; members view change as a threat to prestige and security of their supervisor; change is neither voluntary nor requested by the organizational members; and employees perceive threats to their expertise, status, or security (Gordon 1983).

The introduction of precision assembly processes into the aerospace factory is quite problematic because it dramatically alters the existing responsibilities and power relationships not only within the manufacturing organization, but between the manufacturing and design organizations as well.

*Resistance from within the manufacturing organization.* Some groups within manufacturing will acquire additional responsibilities and resources as a result of the introduction of precision assembly, and their value and status within manufacturing will rise. Fabrication and Manufacturing Research and Development are two organizations for whom the implementation of precision assembly will mean large increases in responsibility. If the individuals within these groups are not properly trained and compensated for their additional job responsibilities, or if they were content with their role in the previous organization, this increase in responsibility could bring added stress and opposition to change. Other groups will see large decreases in responsibility, and the concomitant loss of power and prestige. As responsibilities are shifted to other parts of the enterprise (e.g., from Assembly and Tooling to Fabrication), manpower and resource commitments will be reduced and opposition to change will grow.

*Resistance from the design community.* Although the MBUs aggregate design engineers and manufacturing personnel within the same organization, two significant

differences between the groups remain. These two differences (in organizational power and in the nature of work performed) both tend to favor the design organization over the manufacturing organization. Because the implementation of precision assembly will minimize these differences, and hence reduce the relative importance of design over manufacturing, resistance from the design community should be expected.

The first major difference between the design and manufacturing communities is the relative amount of power each holds within the organization. As noted in Section 1, the historical basis of competition in the aerospace industry has been the design of the aircraft: payload, range, speed, and efficiency. Because manufacturing issues were never as important to customers as design superiority, the design organization rightfully assumed the more powerful position within the organization. After all, designers controlled the most important part of the business. In a study of an aerospace company, Thomas observed that the ability of design engineers to claim that they manage a critical uncertainty (if not *the* critical uncertainty) facing the organization allowed the design community to translate that claim into organizational power (Thomas 1994). Although customers have recently become more sensitive to manufacturing concerns, the division of power within the organization remains largely unchanged.

The second major difference between the manufacturing and design communities is in the nature of the work they perform. Within aerospace manufacturing firms, product engineers are given the charter to develop innovative and creative solutions to challenging design problems. Manufacturing engineers, on the other hand, are neither expected nor rewarded for such creative thinking. The manufacturing organization is expected to execute the design in a routine and mechanistic fashion, all the while minimizing variability and waste. The sense of imagination, innovation, and risk taking found in the design community is actively discouraged in the operations organization, except under the explicit oversight and approval of the design hierarchy (Thomas 1994).



The implementation of precision assembly will affect the relationship between the design and manufacturing organizations by causing a subtle shift in power from design to manufacturing. Once restricted to merely executing the product design, the manufacturing organization will now define the precision assembly concept, perform statistical preassembly analyses, and set tolerance requirements (among other precision assembly responsibilities). In a very real sense, precision assembly gives control over an important and creative part of the aerospace design process (the setting of production specifications) to the manufacturing organization. Design engineers will resist any such loss in responsibility and power to the manufacturing organization. The effect of precision assembly on each individual organization will be analyzed in more detail in Section 6.4 below.

***Managing the process of organizational change is key***

A key insight of Thomas' work is that early attention to the social impacts of technological change is critical to implementation success. Because technology design and implementation are separated in both time and space, the designers of new process technology rarely solicit input from the intended user community. As a result, new technology frequently confronts the rest of the organization as an exogenous force -- one that can be countered only through overt political action. As Thomas notes, "the resultant frustration, resignation, and boundary warfare will redirect energy that might be expended in experimentation or in innovative design of extant processes and relations into efforts to either channel changes along preexisting paths (i.e., at best incremental improvements) or to resist change altogether" (Thomas 1994).

The point of this discussion is that for many groups within the manufacturing organization, precision assembly will be viewed as a threat to their existing power, prestige, and status. The management challenge is to identify the forces of organizational

and/or individual opposition and develop solutions to eliminate those points of resistance. Managing this process of social adaptation, and tailoring the design of the organization to effectively respond to precision assembly, is something to which management must pay explicit attention if precision assembly is not to be rejected by the organization.

### ***Insights from other industries***

A good deal of insight can be gained by examining recent organizational changes implemented at Chrysler and Xerox, two industry leaders in the implementation of tolerance engineering and precision build processes. At Chrysler, the management and reduction of variation on the highly successful LH program was facilitated by a significant organizational restructuring: the movement towards cross-functional platform teams (Held 1993). The grouping of all functions (design, manufacturing, tooling, purchasing, etc.) into a single, co-located organization increased the rate of information transfer and contributed to the successful management of variation on the LH program. All future vehicle development programs at Chrysler will use similar precision build processes, executed within the now-institutionalized platform teams.

At Xerox, the movement towards cross-functional teams preceded the development and application of precision build processes (Dertouzos, Lester and Solow 1989). But the ability to implement the comprehensive methodology proposed by Parks (1991) at Xerox depends heavily on the existence of these cross-functional product teams. Parks' rigorous quantitative methodology stochastically links customer dissatisfiers all the way back to specific design attributes, identifying the effects of variability at every step of the design and manufacturing process. This boundaryless approach to variability management is best performed in a cross-functional environment like that employed at Xerox.

### **6.3 General organizational context barriers to precision assembly**

In their work on the organizational complexities that create barriers to enacting design for manufacturing (DFM) prescriptions, Liker and Fleischer (1993) identify an organization's goals, values, language and symbols (what they term the organizational context) as an often overlooked but nevertheless critical source of opposition to the adoption of cross-functional processes like DFM. Their framework portrays the organizational context as a set of contingencies that influence the success of management's DFM programs. That is, the success of any DFM prescription like precision assembly depends heavily on the supportiveness of the broader organizational context, and not just on the specific policies and practices which accompany the DFM initiatives.

This section will analyze organizational context barriers using the three-category framework (formal organization, political, and cultural) proposed by Liker and Fleischer. These organizational context barriers will then be supplemented in Section 6.4 by a list of specific implementation misalignments between precision assembly and the existing organization. Together, they detail the full range of organizational challenges facing management in its quest to implement precision assembly processes. (Note: It should be mentioned again at this point that all the observations of organizational relationships were made in the host operations organization during the seven month research period. Although all of these observations and findings may not generalize to other firms in the aerospace industry, Kirkwood (1992) has identified a number of similar barriers in the Fabrication Division of the Boeing Company located in Auburn, WA.)

#### ***Formal organization barriers***

As stated in Section 6.1 above, rigid boundaries still exist between the manufacturing and design organizations, and between functions within the manufacturing organization.

These rigid barriers exist primarily in order to facilitate the retention of functional expertise within strong, independent functional departments. Although the use of cross-functional teams has increased in everything from product design to manufacturing process troubleshooting, these teams are essentially parallel, redundant structures in the organization.

The effectiveness of cross-functional teams is limited if they are not used within an organization with permanent cross-functional structures (Liker and Fleischer 1993). The absence of any permanent cross-functional mechanisms impedes the vital horizontal flow of communication required by the interdependence of tasks in the precision assembly methodology. The tendency to analyze and optimize only a specific, functionally-defined part of the production process is encouraged by the rigid barriers between functions, as is the tendency to look vertically (as opposed to horizontally) for solutions to difficult problems. Both present significant challenges for managers responsible for implementing fundamentally cross-functional processes like precision assembly.

### ***Political barriers***

*Organizational politics.* The implementation of precision assembly will cause political tension within the manufacturing organization as responsibilities and resources are redistributed as required by precision assembly. The use of politics in organizational decision-making is most likely to occur whenever five conditions are present: important decision issues, interdependence of responsibilities, conflicting goals, scarcity of resources, and diffuse distributions of power (Pfeffer 1981). The implementation of precision assembly in the manufacturing organization satisfies all five of these conditions, and political resistance is expected to be strongest in those organizations postulated to lose significant amounts of power (e.g., Tooling and Assembly). In fact, the introduction of new process technology, while seemingly apolitical, has the potential to be among the most effective tools in political struggle inside an organization (Thomas

1994). The political decision-making process is not inherently bad, and indeed can never be completely avoided within industrial organizations, but the end result of such gamesmanship may very well be the subordination of the goals of precision assembly to the parochial interests of the organizations involved.

Precision assembly will also cause political tensions between the design and manufacturing organizations. The historic separation between the two organizations has already been blurred substantially by the successful use of Integrated Product Teams (IPTs), and the widespread implementation of precision assembly will serve to further reduce the distinction between those who create the design and those who execute the design. Because that distinction was what allowed the design community to claim large amounts of organizational power, they will object to further encroachment on what they see as their organizational turf.

*Career Progression.* It was argued above that to be effective, the cross-functional relationships required by precision assembly must be more than just parallel, ad-hoc structures within the organization. But individuals facing permanent assignment to a cross-functional team are being asked to abandon well-defined functional career paths for something without nearly as much definition (Womack and Jones 1994). This uncertainty within individuals will manifest itself as an organizational reluctance to support the proliferation of cross-functional precision assembly teams.

*Layoffs.* Like all aerospace manufacturers, the company which sponsored this research has been affected by the recent downturn in the commercial aerospace business. In 1993 alone, this organization was forced to lay off roughly 15% of its work force. Trying to obtain employee support for new initiatives during such difficult times is never easy. When combined with the observation that precision assembly may result in further reductions in head count, especially in the assembly and tooling organizations, obtaining the necessary employee buy-in may be close to impossible.

### ***Cultural barriers***

Cultural barriers represent a significant challenge for management because they may be difficult to identify, let alone address. Schein (1992) defines culture as "a pattern of shared basic assumptions that the group learned as it solved its problems of external adaptation and internal integration, that has worked well enough to be considered valid and, therefore, to be taught to new members as the correct way to perceive, think, and feel in relation to those problems." Because precision assembly is so fundamentally different from current assembly processes, the adoption of precision assembly will violate (almost by definition) many of the core assumptions developed by the organization in its efforts to build airplanes. Using the framework and terminology provided by Schein, organizational members will tend to resist the adoption of precision assembly because it directly attacks the validity of what has been done for the past thirty or forty years.

Schein (1992) also distinguishes between three levels of culture: artifacts, espoused values, and basic underlying assumptions. Artifacts are the visible products of the group, including such attributes as the architecture of its physical environment, its language, its technology and products, its artistic creations, and published lists of values. Espoused values are those perceptions held within the organization of what ought to be as distinct from what is. Espoused values will predict much of what happens at the level of artifacts, but care must be taken to distinguish between what organizational members say and what they actually do. The third level of an organization's culture, and the one which is most difficult to change, are the shared basic assumptions. Basic assumptions are solutions which have worked repeatedly in the past and have been taken for granted by virtually all organizational members. Behavior inconsistent with these assumptions is simply considered inconceivable.

During the research period, I identified three significant cultural barriers to the implementation of precision assembly. At the level of artifacts, using the framework provided by Schein, there exists a tangible sense in most members of the organization

that their company is the finest aerospace company in the world, producing the highest quality airplanes at costs which permit high returns on investment. Many employees see little reason to enact the type of large scale change offered by precision assembly. At the level of espoused values, an emphasis on meeting schedules has proven so successful in the past that many operations decisions are made with the sole intent of keeping the production line moving. Finally, and potentially most problematic for the implementation of precision assembly, the deeply-rooted sense of responsibility which every employee feels towards the safety of the delivered product may act to inhibit the spread of precision assembly throughout the factory, if for no other reason than existing assembly processes have been *proven safe*, whereas precision assembly is to some degree a venture into the unknown.

*Complacency bred by market dominance.* The company which sponsored this research is generally considered the preeminent manufacturer of commercial aircraft in the world, holding a majority of the world market. Increases in market share realized by some competitors during the last ten years have come mainly at the expense of others in the industry, leaving the host company's market share relatively stable. The sense of urgency and fear of business failure which normally precipitate large scale change in business processes is not evident at this company. The question remains whether this firm can make a large scale change like precision assembly without a prevailing sense of dissatisfaction with the status quo.

*Emphasis on schedule.* Meeting scheduled delivery dates has historically taken precedence over those activities designed to reduce the amount of rejection and rework in the manufacturing process. This focus on meeting schedule is found in every part of the organization, and results in shortage meetings, hot lists, and quick-response action teams. All are designed to keep the production line moving. Precision assembly will require a change in focus from meeting schedule to delivering near-perfect parts and subassemblies. Without this fundamental change in perspective, precision assembly will

create more problems than it solves. The significance of this paradigm shift for the manufacturing organization should not be underestimated.

*Conservative nature of the commercial aerospace business.* The host organization has a very successful track record in building airplanes with its existing assembly processes. The one thing it would never, and should never compromise is the delivered safety and reliability of its products. Although precision assembly does not change the design or functionality of the aircraft structure in any way, opposition to precision assembly may appear (and in fact did appear during the seven month research effort) because of a *perceived* reduction in structural integrity or safety margin. Whether these perceptions are grounded in scientific fact or not, they may very well be sufficient to cause conscientious and responsible employees to oppose precision assembly. For many, there simply is no compelling reason to revamp assembly processes which have produced safe and reliable airplanes for the past fifty years.

#### **6.4 Specific implementation misalignments with precision assembly**

This section will conclude the discussion of organizational barriers to precision assembly by examining the specific implementation misalignments between the precision assembly methodology and the organization in which that methodology will be used. In a series of case studies, Leonard-Barton found three major categories of misalignments between new technologies and their host organizations: technical misalignments, delivery system misalignments, and misalignments between the technology and the job performance criteria of those using the technology (Leonard-Barton 1988).

##### ***Technical misalignments***

Technical misalignments occur when the proposed technology is not well suited for the operational environment in which it is introduced. In the case of precision assembly,



the proposed methodology requires a level of process knowledge and understanding in the fabrication, measurement and design organizations which does not currently exist. Jaikumar and Bohn (1986) provide a useful framework for an analysis of the different stages of process knowledge within the manufacturing organization. Their framework is a continuum ranging from immature processes with unpredictable outcomes to those whose nature has been scientifically characterized and whose outcomes are known with a high degree of certainty.

In addressing the technical misalignments caused by the implementation of precision assembly, it is important to understand that inadequate levels of process knowledge exist in the manufacturing organization not because of any willful neglect of responsibility, but simply because the present state of knowledge was adequate to meet existing assembly requirements. For example, the characterization of fabrication processes to the degree required by precision assembly was never required because the assembly tools were always relied upon to set the precise configuration of the structure. It is the movement towards precision assembly which will require deeper levels of understanding in fabrication, measurement, and design processes. And linking back to an argument first made in Section 3, it is this motivation to acquire deeper levels of process understanding which will be the driving force behind real improvements in existing SPC and HVC programs. For precision assembly to succeed, the technical misalignment between what the methodology requires and what the production and design processes can provide must be eliminated.

*Fabrication processes.* The introduction of precision assembly places extraordinary requirements on the fabrication organization. The fabrication of parts for the aircraft floor structure described in Section 5 demonstrated that the fabrication organization does not currently have the capacity of capable processes to produce any significant volume of precision assembly parts. An initial lack of sufficient process discipline resulted in rework and waste during the fabrication of those detail parts. These processes were

eventually made capable after all sources of process variability were identified and eliminated. Additional resources will have to be dedicated to similar efforts at process characterization in order to develop a set of manufacturing processes capable of meeting required precision assembly tolerances.

*Measurement processes.* One of the key observations in the description of the precision assembly methodology provided in Section 4 is that measurement processes may become a bottleneck in the precision assembly factory. Many factors contribute to the potential bottleneck status of the measurement function: the complexity of many aerospace structures, the use of extremely tight tolerances, the requirement to inspect and accept 100% of production output, and a lack of measurement tools capable of performing rapid and accurate measurement of large numbers of structures. This lack of measurement tools capable of meeting precision assembly requirements can be directly attributed to the novelty of these requirements. No significant effort has been put forth towards the development of such tools because the *need* for such tools has never been apparent. Until such measurement technologies are in place, the use of precision assembly techniques on other structures will be restricted due to capacity limitations in the measurement organization.

*Design processes.* Statistical preassembly tools like the one used to analyze the aircraft floor structure in Section 5 are not yet sufficiently characterized to be deployed throughout the organization. While they do provide the designer with additional analytical capabilities, the limitations of such tools (inability to model flexible structures, inability to model assembly compliance, etc.) are significant. Further testing and verification of different statistical preassembly software tools should be performed before one is selected for widespread use.

### ***Delivery system misalignments***

Delivery system misalignments occur when deficiencies in the way a technology is introduced into an organization act to limit the efficacy of that technology in the user environment. As Leonard-Barton points out: "... a misalignment between the technology and the system through which it is delivered to users is not the simple technical issue it masquerades as. Inadequacies for which the developers generally have no direct responsibility but that users may blame on the technology can lead users to reject, underuse or even sabotage the innovation" (Leonard-Barton 1988). In the cases studied by Leonard-Barton, an inadequate delivery system surfaced repeatedly as a seriously underestimated and hence undermanaged misalignment.

Since the proposed precision assembly methodology has never been introduced into the aerospace production environment on a widespread scale, misalignments in the delivery system can only be postulated based on the most likely delivery mechanisms. I see two potential problems in the way precision assembly might be introduced into the organization. The first is a tendency to prematurely select overly-complex assemblies resulting in a failure of the precision assembly process. Failure of the process may be attributed incorrectly to the process of precision assembly, leading to organizational opposition to the implementation of the methodology on even simple structures. The second problem centers on the very prospect of introducing such a cross-functional methodology into an organizational structure without permanent cross-functional relationships. Deficiencies in the execution of the methodology caused by the absence of horizontal communication within the organization may very well be blamed on the methodology and not on the environment in which the methodology is executed.

### ***Misalignments in the technology and job performance criteria***

Misalignments between the technology and the job performance criteria of those using the technology can also lead to implementation barriers. The response of different

organizational members to new technologies or processes, and their subsequent embrace or rejection of that technology, is dependent primarily on how that technology is seen to impact their individual job fate (Liker, Roitman, and Roskies 1987). Management cannot expect the work force to commit to new technology initiatives when those initiatives threaten their perceived well-being in the organization.

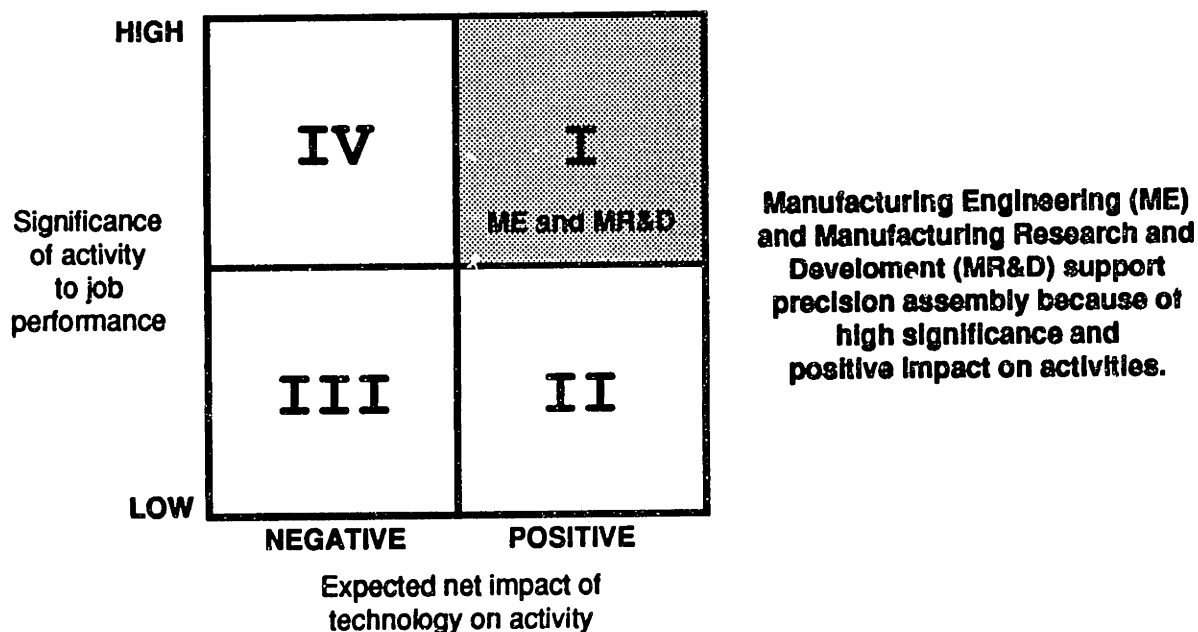
In order to understand the impact of precision assembly on the different groups within the manufacturing organization, the value misalignment model proposed by Leonard-Barton (also used earlier in Section 3) will be employed. Leonard-Barton identifies two generic dimensions of performance criteria which interact with technology to produce misalignments: the *significance* of the technology to the job performance criteria of the activity or task, and the nature of the *impact*, whether positive or negative (Leonard-Barton 1988).

The effect of the technology will be high on the significance axis if it directly affects the criteria by which an individual's success is judged. If the effect is minimal, or the activities affected are not central to the individual's performance review, the significance would be low. As can be seen in Figures 6.4 through 6.6, the effects of precision assembly on all facets of the manufacturing organization will be high on Leonard-Barton's significance axis. The nature and division of work in the manufacturing organization will change dramatically. The Tooling and Assembly organizations will lose large parts of their business. Fabrication and Quality Assurance will be challenged to put into operation the new processes required by precision assembly. Manufacturing Engineering and Manufacturing Research and Development will be relied upon to develop the technologies which will make precision assembly a reality. As precision assembly forces changes in job requirements throughout the factory, workers will find themselves performing different tasks and being measured in different ways.

The issue of whether such changes are positive or negative for the employee is addressed on Leonard-Barton's impact axis. Technologies which result in lost time, lost

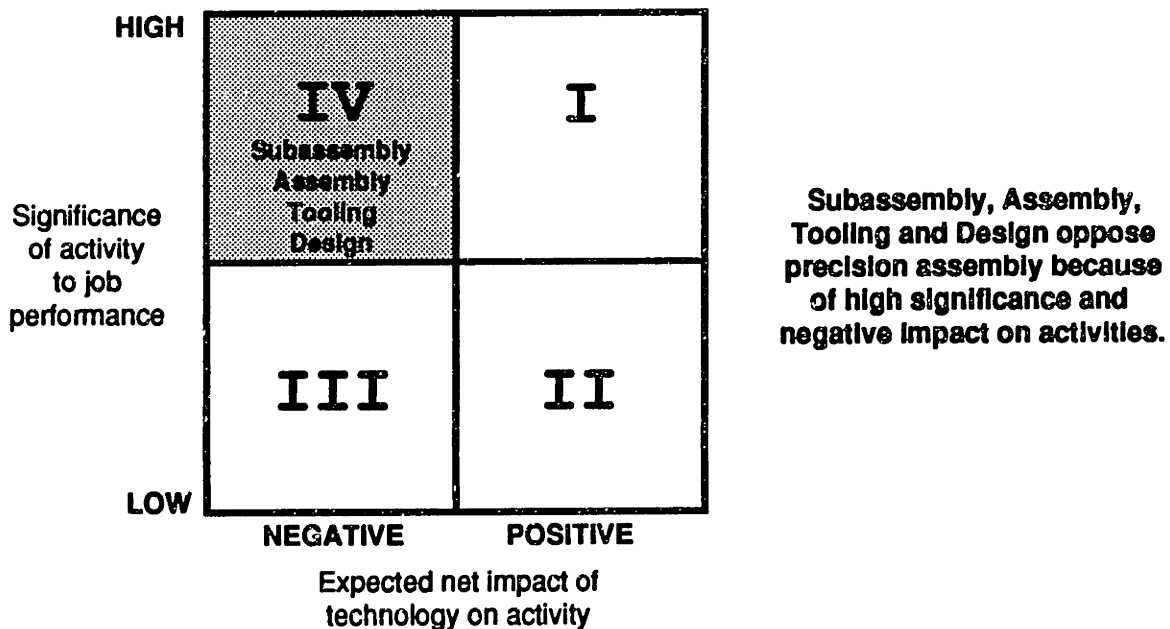
skills, or unpleasant routines have negative impacts. Technologies which increase skills, improve quality, or provide a higher status level in the organization are rated as positive. Precision assembly impacts the groups within the manufacturing organization in the following way:

*Positive Impact:* Manufacturing Engineering (ME) and Manufacturing Research and Development (MR&D). Figure 6.4 places the ME and MR&D groups in Quadrant I, for High Significance and Positive Impact. ME will most likely be given the responsibility within the manufacturing organization of coordinating and controlling the practice of precision assembly. They will be called on to do everything from performing statistical preassembly analyses (in order to apply tolerances to engineering drawings) to managing the flow of parts and assemblies through the precision assembly factory. The technical capabilities of MR&D will be leveraged in the development of new fabrication and measurement processes specified by ME. It is evident that the status and power of these two organizations will rise as they become even more critical to production.



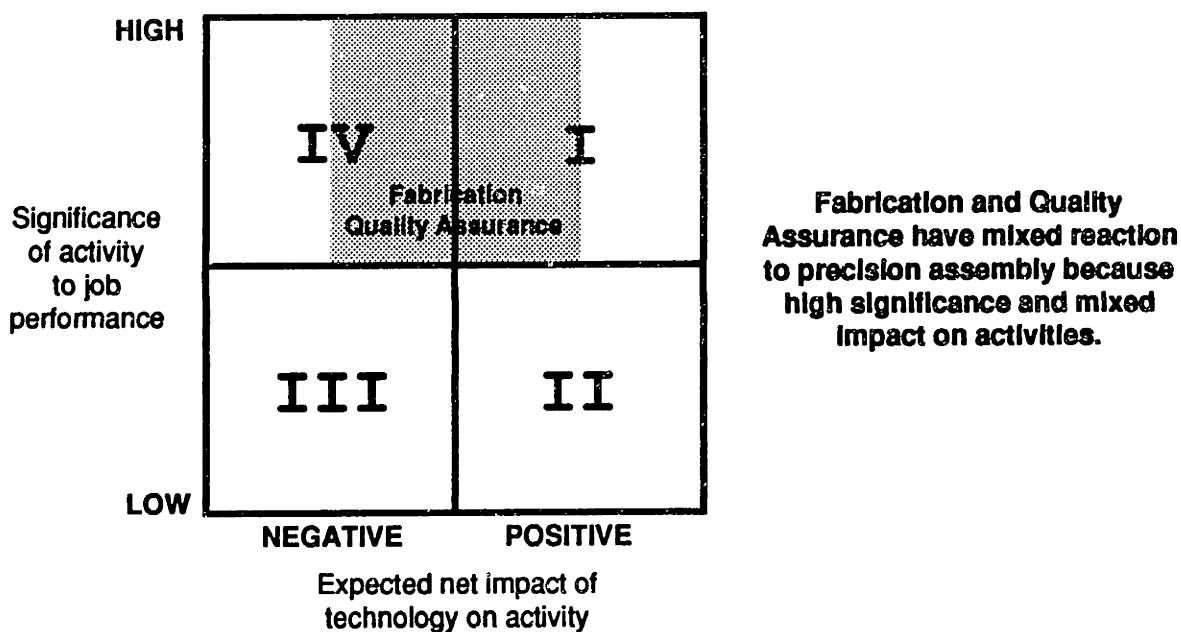
**Figure 6.4 Manufacturing Engineering and Manufacturing Research and Development tend to support precision assembly**

*Negative Impact:* Subassembly, Assembly, Tooling and Design. Figure 6.5 depicts these four groups as the groups with the most to lose in the precision assembly factory, where the impact on their jobs is both significant and negative. This is the quadrant where the biggest implementation misalignments exist, and where the majority of management attention will have to be focused. Precision assembly will reduce many of the skill and manpower requirements in subassembly, assembly, and tooling. As more structures are built using precision assembly techniques, requirements for tool construction and maintenance will decrease. Precision assemblies will require less custom-fit assembly procedures, reducing the need for skilled assembly mechanics. The spread of precision assembly will most likely mean that design engineers will have to cede some of their responsibility and power to the manufacturing organization. These four groups will rightly see the adoption of precision assembly as a threat to their current status in the organization. Resistance will be greatest in these organizations.



**Figure 6.5 Subassembly, Assembly, Tooling, and Design tend to oppose precision assembly**

*Mixed Impact: Fabrication and Quality Assurance.* Figure 6.6 shows Fabrication and Quality Assurance without a clear negative or positive impact. The rationale for this classification is that while precision assembly will certainly increase the importance of these groups within the factory, it will provide significant challenges for them as well. The additional effort required in Fabrication and Quality Assurance, coupled with their lack of current capability to perform many of the jobs required of them, will lead to high levels of management attention and stress. The additional resources and power afforded them will tend to offset the stress, but the net impact is predicted to be somewhere in the middle of the impact spectrum.



**Figure 6.6 Fabrication and Quality Assurance have mixed reactions to precision assembly**

**Summary**

The specific implementation misalignments (technical, delivery system, and value systems) and organizational context barriers (formal organizational, political, and

cultural) are real issues for management to consider. This section has attempted to articulate exactly why these forces present in the existing organization will act to oppose the implementation of precision assembly. Section 7 will offer a number of organizational prescriptions to help overcome the barriers described in this section. If the organizational barriers identified here can be removed, the implementation process can be undertaken with a higher probability of success.



## **Section 7. Implementing precision assembly**

It is a fundamental conclusion of this research that the introduction of the proposed methodology for precision assembly will require significant change in aerospace manufacturing organizations. It is evident from the extensive list of organizational barriers identified in Section 6 that attempting to execute the proposed precision assembly methodology within the existing organizational structure will be unsuccessful. In addition to recognizing the *need* for change, however, management must also determine the *extent* of change required by the implementation of precision assembly. The specific implementation misalignments, coupled with a more general set of organizational context barriers, will compel management to make large-scale changes in the design and operation of their manufacturing organizations. Only through dramatic changes to the status quo will the postulated benefits of precision assembly be realized.

I describe in Section 7.1 a general philosophy of how to implement the proposed methodology of precision assembly. This philosophy has two objectives for the design of the organization: the near-term performance of the precision assembly process proposed earlier, and the long term ability to refine and improve the precision assembly methodology. In Sections 7.2 and 7.3, I propose new, more effective fabrication and assembly organizations for the precision assembly factory. In the fabrication organization, manufacturing cells will be proposed as a means for achieving precision assembly success. Each cell will be staffed by a cross-functional team dedicated to the high-quality production of a single family of parts. In the assembly organization, dedicated cross-functional teams focused on specific precision assemblies are proposed to gradually replace the existing functional organization. Finally, in Section 7.4, I provide some proposals for managing the interface between design and manufacturing in light of the special requirements created by precision assembly.

## 7.1 Philosophy of implementation

Before moving to specific recommendations for changing the fabrication and assembly organizations, it is instructive to elaborate on the general philosophy of implementation which should guide much of the process of organizational redesign. I will make the argument in this section that the fundamental nature of precision assembly will require significantly more than a traditional, autocratic implementation strategy. The ability of the organization to make precision assembly work and to constantly improve the precision assembly process will hinge on the commitment of everyone affected by precision assembly. In short, the success hinges on *every* employee and *every* organization in the aerospace factory. The introduction of precision assembly must proceed along a path which ensures this commitment of all members of the organization. Individuals must be given a voice in the redesign of their jobs and must be permitted some control over their destinies in the precision assembly factory. The authoritarian approach used to spread HVC and SPC practices through the factory is not compatible with achieving the levels of commitment required by precision assembly.

Beckhard proposes five operational goals for organizational development efforts which provide a useful framework from which to discuss the general philosophy of implementing precision assembly (Beckhard 1969). Achieving the required degree of employee commitment (and therefore the very success of precision assembly) will depend on management's ability to effectively achieve all five of these goals. Beckhard's five goals, discussed here in the context of precision assembly, are:

*To develop a self-renewing, viable structure that can organize in a variety of ways depending on tasks.* An organization's form should follow its function, meaning that the design of an organization should depend on the tasks it will perform rather than be an inflexible structure into which new tasks must be assimilated. A cross-functional

structure is therefore considered appropriate for the efficient execution of the cross-functional precision assembly process. In addition, some researchers have emphasized the need during organizational redesign efforts to develop organizational capabilities, not just specific products (Trist 1976). In other words, the redesign effort should not simply be focused on how best to implement precision assembly in the short term, but how to design an organization which will be able to continuously execute, modify, and improve the precision assembly methodology for all time. This second point is especially critical because as the manufacturing organization becomes more familiar with the methodology and with its own capabilities, opportunities to improve the methodology will be revealed. In short, the organization must be capable of modifying the methodology to address emerging capabilities and requirements.

*To optimize the effectiveness of both the stable (the basic organization chart) and the temporary systems (the many projects, committees, etc. through which much of the organization's work is accomplished) by built-in, continuous improvement mechanisms.* Management must design mechanisms to provide continuous feedback on the performance of all precision assembly tasks. Because the organization has little to no experience in the performance of the precision assembly methodology, structures and procedures must be put in place through which best practices can be studied, documented and disseminated through the organization. Measurement of the resources consumed and time spent in executing the process will allow organization-wide benchmarks to be established to facilitate continuous improvement.

*To move towards high collaboration and low competition between interdependent units.* Beckhard's research has identified one of the major obstacles to effective organizations as the amount of dysfunctional energy spent in inappropriate competition -- energy that is therefore not available for the performance of tasks more central to the

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mission of the organization (Beckhard 1969). Because the nature of the precision assembly methodology is so cross-functional, and because the current organization lacks any permanent cross-functional structures (as detailed earlier in Section 6), the implementation of precision assembly into the existing organization without any substantive changes will result in significant amounts of dysfunctional energy. One potential way to foster high levels of collaboration between interdependent and competing units is to aggregate those units into a single organization with a single mission and leader. Indeed, this is precisely what is proposed in Sections 7.2 and 7.3 below.

*To create conditions where conflict is brought out and managed.* Schein defines organization effectiveness in relation to what he calls “the adaptive coping cycle,” or how well an organization can adapt and cope with changes in its environment (Schein 1965). It is essential that conflicts over precision assembly be brought to the surface and managed in an environment free from intimidation, threat, and fear. An honest and frank discussion of issues related to the implementation of precision assembly is required because the opposite (management by intimidation) tends to undermine good communication, reduce flexibility, and stimulate self-protection rather than concern for the total system. If organizational members are likely to resist change because of fear and anxiety about their roles in a new organizational context, an implementation process high in individual participation and involvement, but facilitated and supported by upper management, makes a good deal of sense (Kotter and Schlesinger 1979).

*To reach the point where decisions are made on the basis of information source rather than organizational role.* One of the conditions in organizations which Schein views as essential for effective coping with change is the ability to take in and communicate information reliably and validly (Schein 1965). Because most of the

knowledge in the organization is found on the factory floor, with the workers actually adding value to the customer's product, it is essential that those workers be allowed to communicate information and make decisions based on their knowledge and experience (Welliver 1988). The decentralization of decision-making authority is even more critical in the precision assembly factory because the integrity of the entire concept depends on so many different decisions made within the context of individual areas of expertise. It is when decisions are made by those with organizational power and not by those with the relevant information that mistakes are made.

Getting decision-making authority into the hands of organizational members with the knowledge to make the right decision is not a simple task. In studying various ways to introduce change to organizations, Greiner has identified that virtually all strategies can be grouped on a power distribution continuum (Greiner 1970). Power strategies span the range from unilateral approaches (management directs every phase of the process) to delegated approaches (individual organizational members define and enact their own change processes). Somewhere in between these two extremes is the best approach for the implementation of precision assembly. In other words, precision assembly teams will design better concepts and gain a greater sense of ownership (hence improving the chance of implementation success) if they are permitted a good deal of flexibility to make decisions within the broad context of the methodology described in Section 4.

## **7.2 Building the new fabrication organization**

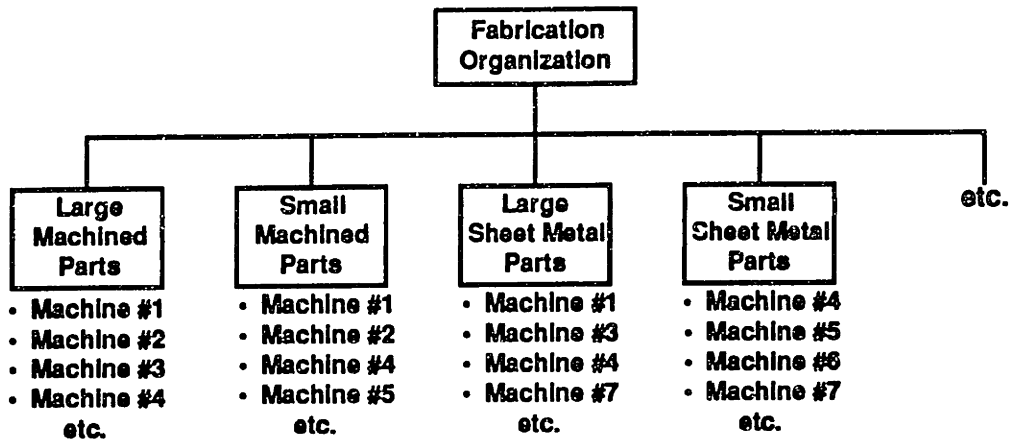
### ***Design of the new fabrication organization***

Two major changes should be made to the existing fabrication organization in order to facilitate the implementation of precision assembly: the factory should be re-configured into manufacturing cells, and permanent cross-functional teams should be

created to operate each manufacturing cell. These two changes are motivated directly by the philosophy outlined in Section 7.1. The decentralization of knowledge and decision-making authority into segments of the manufacturing organization focused on key precision assembly processes will facilitate the immediate and efficient execution of precision assembly and lay the groundwork for continuous improvement later on.

*Cellular manufacturing.* Group technology approaches are used to create subsets of the business for which manufacturing cells make sense. The majority of the fabrication business can be arranged into groups of parts which have similar attributes and which go through similar processing steps. The creation of part families like “small machined parts,” “small sheet metal parts,” “large extruded parts,” etc. as shown in Figure 7.1 will facilitate the introduction of manufacturing cells. The processes necessary to manufacture all parts in a specific part family are co-located within each manufacturing cell. In some rare cases (due to multi-cell economies of scale or environmental regulations, for example), parts may have to travel outside the cell to a centralized processing facility. Pratt and Whitney is one aerospace manufacturer who has recently committed to such a cellular reorganization of their fabrication processes (Aerospace Propulsion 1992).

*Permanent cross-functional relationships.* Each team operating a manufacturing cell should contain all necessary operational and support functions. All functions within the cell team, from machine operations to manufacturing planning to process engineering, will report directly to the cell leader. In the interest of intra-team flexibility, all team members will be expected to perform duties outside of their narrowly-defined functional specialties.



**Note: Cellular organization based on PART FAMILIES**

**Figure 7.1 Proposed cellular fabrication organization**

The desire to maintain functional depth and expertise can be achieved within a permanent cross-functional structure. Establishing smaller, more focused functional “schools” through which individuals assigned to cross-functional teams would rotate during the course of their careers can facilitate the development and retention of functional expertise. Rather than actually performing a specific set of functional tasks, these “schools” would be responsible for defining and disseminating to all cross-functional groups the preferred process for the performance of all functional tasks (Womack and Jones 1994).

*Advantages.* The advantages to a cellular manufacturing approach have been well documented (see, for example, Schmenner 1988). Indeed, one industry study documents the dramatic advantages of cellular manufacturing as: reductions in work-in-process inventory of 90%, reductions in lift truck requirements of 90%, reductions in machine downtime of 75%, reductions in defects of 75%, reductions in plant space requirements

of 75%, and increases in personnel productivity of 30 to 50% (Tooling and Production 1992).

Cellular manufacturing and permanent cross-functional teams will enable precision assembly in a number of important ways. Cellular manufacturing will provide the necessary focus on quality and defect reduction. Turf battles and non-value added effort spent assigning blame are reduced by combining all those who affect the final configuration of a part into a single organization, with a single leader and a single purpose: the production of high quality parts. The grouping of like parts will allow larger production runs within a given process and the associated opportunity to develop deeper levels of process understanding. Fabrication expertise for a given part family will be entirely contained within that family's manufacturing cell, and not distributed across many different functional organizations.

Manufacturing cells will also increase the rate and quality of inter-process communication and learning. By linking sequential process steps tightly within a manufacturing cell, problems in the entire manufacturing process can be identified and solved in a timely manner. The horizontal communication required to maintain configuration control of precision assembly parts as they move through different fabrication processes is thus facilitated by a cellular approach. The learning that occurs within the cell will not only increase the accuracy with which current generation parts are fabricated, but will improve the quality of information which the fabrication organization brings to Integrated Product Teams during the design of next generation products.

### ***Implementation of the new fabrication organization***

Management's first task in the implementation process must be to spread dissatisfaction with the status quo through the entire organization (Spector 1989). The willingness of employees to accept large scale change will depend on their relative lack of comfort with the status quo. If they can be convinced that competitive pressures are



forcing the dramatic changes in the aircraft manufacturing process, as indeed in this case they are, they will be much more willing to accept responsibility for making the changes associated with precision assembly happen.

The implementation of precision assembly must proceed in a manner very different from business as usual. Cell leaders must be appointed based on skill and ability, and not on seniority. In some cases, they may have to be brought in from outside the company in much the same manner employed in recent years at Pratt and Whitney (Aerospace Propulsion 1992). The reporting structures of all support groups must be permanently changed to reflect the new cross-functional organizations. Although these new cell leaders will be directed to implement precision assembly, they also will be given a great deal of flexibility over how best to implement precision assembly within their individual manufacturing cells. That flexibility must also extend into personnel decisions, where cell leaders are given the authority to hire and fire in order to facilitate the smooth introduction of precision assembly into their organizations.

Segmenting the business base of the factory into an appropriate number of part families and implementing manufacturing cells should proceed without delay. Dividing the fabrication organization into manufacturing cells must occur fairly rapidly as it is a necessary precursor to a plant-wide implementation of precision assembly, primarily because of the focus on quality that manufacturing cells will provide. The more experience the organization develops with manufacturing cells prior to the full-scale adoption of precision assembly, the greater the chance of success. Although the adoption of cellular manufacturing approaches can be justified based solely on the documented cost, throughput, and quality advantages described above, it is important to understand the vital link between manufacturing cells and precision assembly.

Management must measure and control the process of implementation very carefully. Benchmarks of manufacturing cost (to the degree that existing accounting systems permit the accurate determination of cost), time, and quality need to be established prior to the

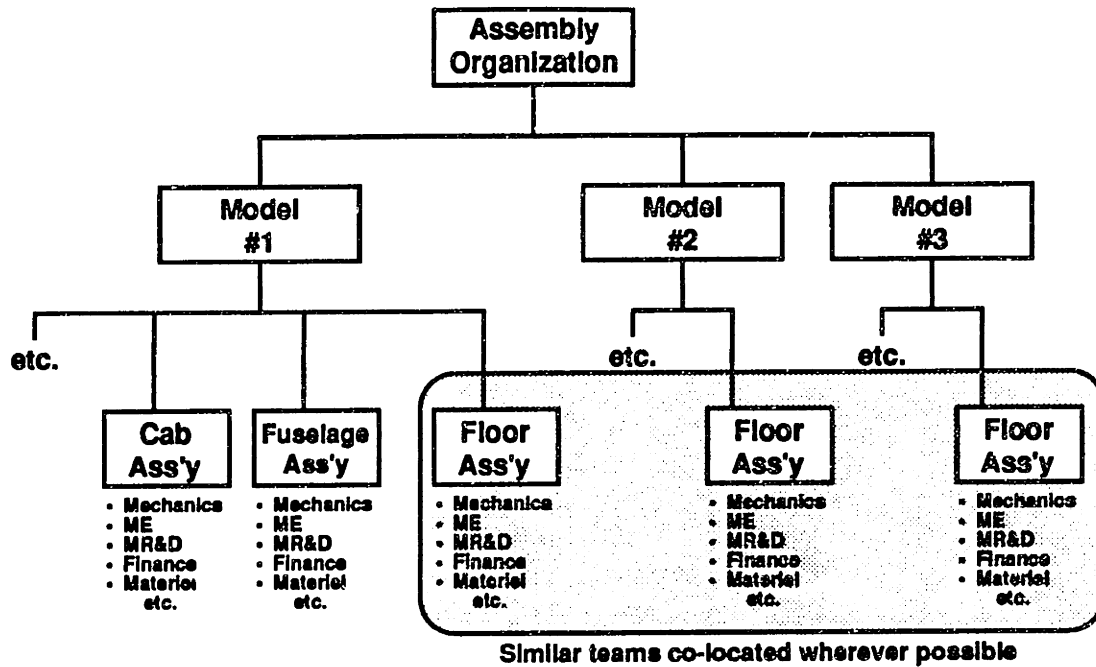
creation of any manufacturing cells. The very time it takes to establish a cell (assemble a team, move the process equipment, resume production, etc.) should itself be benchmarked, studied, and reduced. Cell throughput and cycle time should be measured and continuously reduced. Manufacturing cost and quality should be compared to pre-cell benchmarks to justify the creation of additional manufacturing cells.

### **7.3 Building the new assembly organization**

#### ***Design of the new assembly organization***

The first step in the creation of a new assembly organization is the elimination of the artificial boundary between the subassembly and major assembly organizations, as seen in Figure 7.2. The dependence of the configuration of the final assembly on the configuration of all constituent subassemblies and detail parts makes any distinction between the subassembly and major assembly organizations problematic. The new assembly organization will have complete responsibility for the construction of final assemblies with the minimum use of assembly tools. In the case of the aircraft floor structure described in Section 5, a single organization will have responsibility for the construction of the entire floor, including all intermediate subassembly processes.

It is this new assembly organization that will direct and control the precision assembly process. In addition to the actual assembly of the structure, this organization will be responsible for selecting a precision assembly concept, performing the statistical preassembly analyses and placing tolerances on the engineering drawings. Giving responsibility for the control of the precision assembly process to the assembly organization will enforce the notion that the requirements of precision assembly should be driven from the assembly level down towards fabrication, and not vice versa. The fact that individual cells are now responsible for accumulating and retaining process



**Figure 7.2 Proposed cross-functional assembly organization**

knowledge related to a specific set of parts will facilitate the transfer and use of process knowledge during the definition of the precision assembly concept, if for no other reason than the assembly organization will now know exactly where to obtain such process knowledge. It is vital that the interface between fabrication and assembly be managed well. Factory management must ensure that the fabrication organization understands its important role of developing, documenting, and transferring its process knowledge to its customer, the precision assembly teams.

The cross-functional responsibilities of this organization will require a permanent cross-functional structure, much like that seen earlier in the fabrication organization. Individuals with skills in product engineering, assembly, MR&D, manufacturing engineering, finance, and quality assurance will be permanently assigned to an assembly cell organization and report directly to a cell leader. Specific individuals or groups will

not be constrained to these functional roles, however, but rather will be expected to move between a few different roles as requirements dictate. Placing all of the assembly-related functions within a single, co-located organization allows the assembly group to analyze within a cross-functional environment how well their design worked and make real-time improvements. The process of modifying the precision assembly concept and requirements, especially once real world limitations in manufacturing processes have been identified, will proceed much more efficiently if all affected functions are contained within a single organization.

Finally, once the organizational changes have been completed, provisions should be made for close coordination between like functions in different airplane assembly organizations (e.g. the floor assembly teams within the different airplane groups as seen in Figure 7.2). Chrysler has had a great deal of success at its Technology Center by positioning similar functions on different vehicle platform teams in close proximity to one another (Womack and Jones 1994). At the Technology Center, a cross-functional platform team will occupy an entire floor (facilitating inter-function communication), but similar functions like engine and transmission design on different platform teams are located directly above and below one another (facilitating intra-function communication as well). Frequent communication between teams executing precision assembly concepts on similar structures on different aircraft models will help will increase the rate of organizational learning and help identify and disseminate best practices in the execution of precision assembly concepts.

### ***Implementation of the new assembly organization***

The implementation of the new assembly structure needs to occur much more gradually than the change to cellular manufacturing within the fabrication organization for three reasons. First, the proposed organization is optimized for use with precision assembly techniques and their unique requirements. There is no compelling reason to

revamp those parts of the assembly organization focused on the production of standard, non-precision assembly hardware. The methods and techniques employed in the existing organization have the proven capability of producing safe and reliable hardware. In other words, the new organization should be built up around the precision assembly structures as they are gradually introduced into the factory.

Second, the adoption of precision assembly will have a significant and negative impact on the daily job tasks of most workers in the assembly organization as noted in Section 6. Management must be completely forthcoming with those employees who lose power, status or comfort. Indeed, Peters and Austin (1985) view management integrity as an essential part of managing any major systems change. A phased implementation which permits a period of adjustment to the new processes is preferred over wholesale changes because it lessens the probability of outright rejection of the precision assembly methodologies.

Third, the execution of the precision assembly process needs to be studied and perhaps modified in an operational context in more detail before commitments across the entire product line are made. Leonard-Barton has identified the importance of such carefully-managed beta test sites in ascertaining the reaction of the organization to new technologies (Leonard-Barton 1988). Only after significant organizational changes like the one proposed here are implemented on a small scale and studied should management consider proliferating that change throughout the entire organization.

#### **7.4 Managing the interface between design and manufacturing**

The negative effects on manufacturing cost and product quality of rigid boundaries between the design and manufacturing functions has been well documented (see, for example, Hayes, Wheelwright and Clark 1988). Thomas (1994) concludes that many of the organizational prescriptions designed to bridge the gap between design and

manufacturing simply do not go far enough. The application of organizational techniques like matrix management or the use of heavyweight program managers rarely provide the opportunity to build the manufacturing organization into a source of competitive advantage for the firm.

Within this particular firm, the successful use of Integrated Product Teams on recent programs has helped to bridge the gap between design and manufacturing during the product design phase and has resulted in significant reductions in engineering changes and rework during program launches. But the mission of the Integrated Product Teams, to design the aircraft using input from everyone from designers to manufacturers to customers, is now complete and for the most part the teams have been disbanded. The execution of that *cross-functional* design is occurring in the standard, *functional* manufacturing organization.

The implementation of precision assembly will serve to highlight the interdependence between design and manufacturing not only during the design of the product, but also during its manufacture. Rapid and frequent iterations will require that designers and manufacturers work together well past the point where the design is frozen. Indeed, the opportunity that precision assembly provides to continuously improve the manufacture of the product (through different precision assembly concepts, through the application of new production technologies, etc.) may compel high levels of interaction between the two groups for the life of the program.

There are a number of steps which management can take to ensure that the newly developed knowledge (and power) of the manufacturing organization is used in a productive way with regard to the design community. First, manufacturing management should leverage the creation of the permanent cross-functional teams by emphasizing the importance of a complete systems or process perspective. The co-location of all functions affecting product configuration presents an excellent opportunity to analyze the systemic effects of process variability on different parts of the design. This information

can then be communicated to the design organization to assist them in the creation of more robust designs.

Second, the manufacturing organization should request that design engineers participate in the development of precision assembly concepts for current generation products. Their input with regard to the functionality of the design will be invaluable. For next generation products, the manufacturing organization must send its most qualified people to the Integrated Product Teams, armed with the most recent information about manufacturing capabilities. The key difference now is that the implementation of precision assembly has forced the manufacturing organization to develop a set of capable fabrication processes which may very well *enable* improved product designs (thinner gauge material, reduced fastener count, etc.). A manufacturing organization which can not only respond to demands placed on it but also stimulate product innovation and change is a potential source of significant competitive advantage (Thomas 1994).

### ***Summary***

On the surface, precision assembly appears to be fundamentally a process of *technological* change. The most difficult part of the implementation process, however, will be managing the impacts of precision assembly on *organizational* members and structures. This section has detailed an implementation philosophy and provided a series of recommendations which, if enacted, should enable those organizational barriers to be surmounted. The fundamental conclusion reached by Leonard-Barton (1988) after her extensive study of technological innovation is directly relevant to those wishing to implement precision assembly processes in the commercial aircraft industry. To wit, management must recognize and assume responsibility for both technological and organizational change if new process technologies are to be incorporated efficiently into the user organization.





## **Section 8: Conclusions**

### ***Research findings***

This research effort demonstrated the technical feasibility of assembling aerospace structures without assembly tools. Other results of this research effort include:

*Precision assembly will focus existing HVC efforts.* Substantial reductions in hardware variability through the implementation of standard hardware variability control (HVC) programs have proven elusive in the aerospace industry. Precision assembly can provide the important focus required by HVC programs and drive real progress in the reduction of variability.

*Precision assembly drives the development of more capable fabrication processes.* The successful implementation of precision assembly processes will require the identification and elimination of fabrication process deficiencies. The development of new fabrication capabilities can then be leveraged not only to better produce existing structures, but also to develop superior next-generation product designs. In this sense, the manufacturing organization can become a source of significant competitive advantage for the aerospace firm.

*Process discipline is the key to precision assembly.* Process capability, and not machine capability, is the key to precision assembly. In many cases, increased process discipline in the factory will satisfy any precision assembly requirements and avoid expensive and unnecessary investments in capital equipment. The tight tolerances required to assemble the aircraft floor structure were all met on existing fabrication machines after the identification and control of critical process parameters.

*Fast, accurate measurement processes are critical.* Measurement processes will become a bottleneck in the precision assembly factory. The development of faster and more accurate measurement processes, especially for large and complex structures, is a critical part of implementing precision assembly.

*The proposed precision assembly requires a 3D digital product definition.* It is absolutely essential that all structures be defined in a 3D digital environment if they are to be built without assembly tools. Statistical preassembly tools, a key part of the precision assembly process, can only be used on structures with a 3D digital definition. The precision assembly methodology proposed here should not be attempted without such a 3D digital definition.

*The organizational impacts of precision assembly will be just as difficult (if not more difficult) to manage as the technological impacts.* In a sense, the extent of the technological challenge of precision assembly can be directly quantified. Design requirements, manufacturing process capabilities, computer analysis tools, etc. are all either known or knowable. Overcoming organizational resistance, particularly when its source and strength are so difficult to determine, is a much more challenging management task.

*Significant organizational change will have to accompany the implementation of precision assembly if its postulated advantages are to be achieved.* The existing, functional organization at most aerospace manufacturing firms is simply not well-suited for the implementation of the cross-functional process of precision assembly. Significant barriers to the successful implementation of precision assembly exist and will only be eliminated through large scale change to organizational structures, policies, and people.

*Management must assume responsibility for leading both technological and organizational change.* An approach focused on both technological and organizational impacts is needed to efficiently introduce precision assembly into the organization. The tendency for management to emphasize the search for solutions to technological problems will address only a fraction of the implementation challenge. The real barriers to implementation are organizational, and management resources must be targeted in that direction.

Knowing that precision assembly techniques can be applied with success in the aerospace industry does not in and of itself provide competitive advantage. The competitive advantage will come from how well the process of precision assembly implementation is managed, and real sustainable advantages will be gained only by those who can execute and implement in a superior fashion. Those firms which think that the implementation of precision assembly is a simple technological problem with straightforward solutions, and which ignore the critical process of organizational change, may very well find themselves worse off than when they started.

### ***Recommendations for future work***

*Develop accurate manufacturing cost models.* The trade-off analyses implicit in the development of any precision assembly concept should be based on manufacturing cost. The lack of comprehensive, accurate cost models for fabrication and assembly processes, however, prevents the effective use of cost as a target objective. Instead, the bases for selecting one precision assembly concept over another centers on the manufacturability of the concept (does the process capability exist to achieve the required tolerances?) and/or the requirements of the design (what does the functionality of the design require?). The

development of effective cost models would be an invaluable tool in helping precision assembly teams understand the ramifications of their design and manufacturing decisions, allowing them to further optimize their concepts in the cost domain so important to the customer.

*Continue to develop statistical preassembly tools for use with CAD systems.* The statistical preassembly tool developed as part of this research effort did not have a direct interface with the computer-aided design systems. Statistical preassembly tools which can be used directly with the solid models in the CAD environment would help further shorten the development time for precision assembly concepts. The limitations of such tools needs to be further examined, especially the impact of not being able to adequately account for flexible parts or compliance during the assembly process. Additional resources should be dedicated to this field of research as it represents one of the key enabling technologies for precision assembly.

*Develop a process to apply precision assembly to hardware designed prior to the widespread use of CAD systems.* The methodology described in this thesis applies only to those structures with complete, 3D digital definitions. Today, however, the vast majority of structures produced in the aerospace industry do not have such digital definitions. Once the cost savings of precision assembly concepts are well established, the development of a process aimed at efficiently creating 3D models for structures designed prior to the use of CAD systems should be undertaken. The cost of digitizing these older engineering drawings and creating the required 3D models by hand may be justified if the downstream manufacturing processes can be sufficiently simplified.

*Develop the measurement technologies required to accept precision assembly structures.* Unless new measurement techniques are developed, the process of accepting

and verifying precision assembly structures will become a bottleneck in the aerospace factory. Without the measurement baseline provided today by the assembly tools, accepting aerospace structures will become a much more complicated process more akin to current (and costly) tool certification processes. The development of faster and more accurate measurement processes, especially for larger and more complex structures, is a point of high leverage in the effort to implement precision assembly. Measurement processes which can rapidly and accurately verify parts and assemblies back to the original engineering data are required if assembly tools are to be removed from the factory.



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## Appendix A: Mathematical formulation of the model

(Source: Shalon 1992)

As shown in Figure A.1, the position of  $O_2$  relative to  $O_1$  is defined by the vector  $\underline{\delta}_{12}$  which has  $X_1$ ,  $Y_1$ , and  $Z_1$  components:

$$\underline{\delta}_{12} = \begin{bmatrix} \delta_x \\ \delta_y \\ \delta_z \end{bmatrix}$$

Figure A.2 shows that the angular orientation of  $O_2$  relative to  $O_1$  can be defined by three Euler angles  $\Phi$ ,  $\theta$ , and  $\Psi$ . The order of the angles is not commutative. The convention is to specify them in the order specified in Figure A.2.

Again referring to Figure A.1, the path to point P can be specified in either of two coordinate systems with vector  $\underline{P}$ :

In the  $O_1$  system:  $\underline{P}_1 = [P_{X1}, P_{Y1}, P_{Z1}]$

In the  $O_2$  system:  $\underline{P}_2 = [P_{X2}, P_{Y2}, P_{Z2}]$

It is also possible to define  $\underline{P}_1$  in the following way:

$$\underline{P}_1 = \underline{T}_{12} \cdot \underline{P}_2$$

$\underline{T}_{12}$  is the transformation matrix consisting of a translation vector  $\underline{\delta}_{12}$  and a rotation matrix  $\underline{R}_{\Phi\theta\Psi}$  along with the homogeneous coordinate 1 in the lower right hand corner of the matrix. The homogeneous coordinate makes  $\underline{T}_{12}$  a symmetric 4x4 matrix and simplifies the matrix multiplication done later.

$$\underline{T}_{12} = \begin{bmatrix} \text{---} & \text{---} & \text{---} & \delta_x \\ \text{---} & \text{---} & \text{---} & \delta_y \\ \text{---} & \text{---} & \text{---} & \delta_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

The translational vector, with components  $\delta_x$ ,  $\delta_y$  and  $\delta_z$ , was defined above. The rotational matrix,  $R_{O_1 O_2}$ , is defined as follows:

$$R_{O_1 O_2} = \begin{vmatrix} \cos\Phi \cos\Psi - \sin\Phi \sin\theta \sin\Psi & -\cos\Phi \sin\Psi - \sin\Phi \cos\theta \cos\Psi & \sin\Phi \sin\theta \\ \sin\Phi \cos\Psi - \cos\Phi \cos\theta \sin\Psi & -\sin\Phi \sin\Psi + \cos\Phi \cos\theta \cos\Psi & -\cos\Phi \sin\theta \\ \sin\theta \sin\Psi & \sin\theta \cos\Psi & \cos\theta \end{vmatrix}$$

Figure A.3 shows that the global position of a point originally specified in a local coordinate system is simply the product of the transformation matrices of the intermediate coordinate systems multiplied by the local vector.

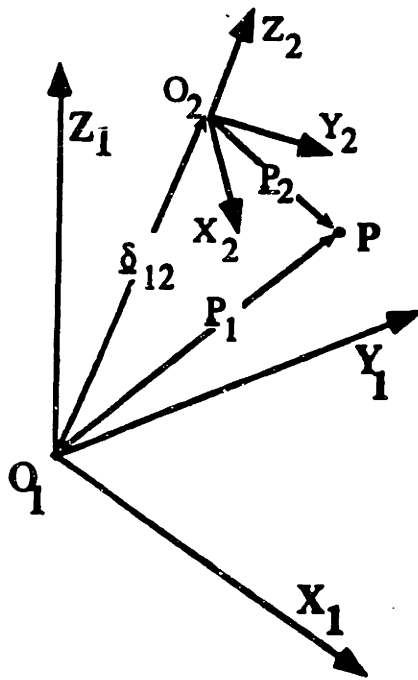


Figure A.1 Defining the path to point P in a global ( $O_1$ ) and local ( $O_2$ ) coordinate system

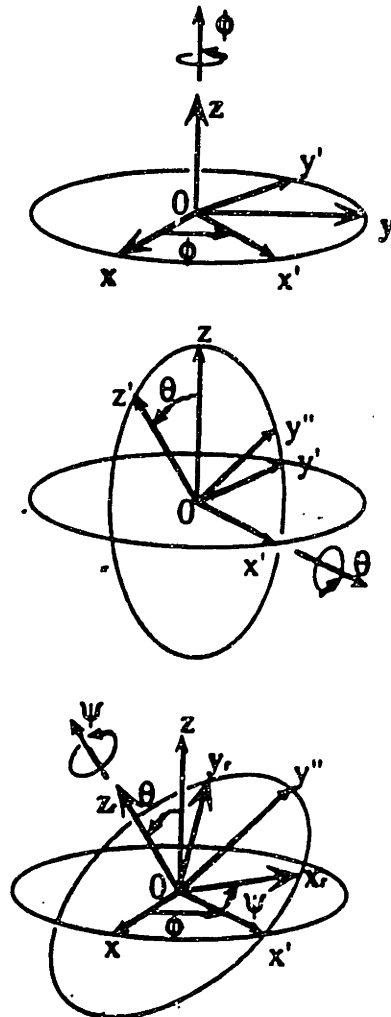
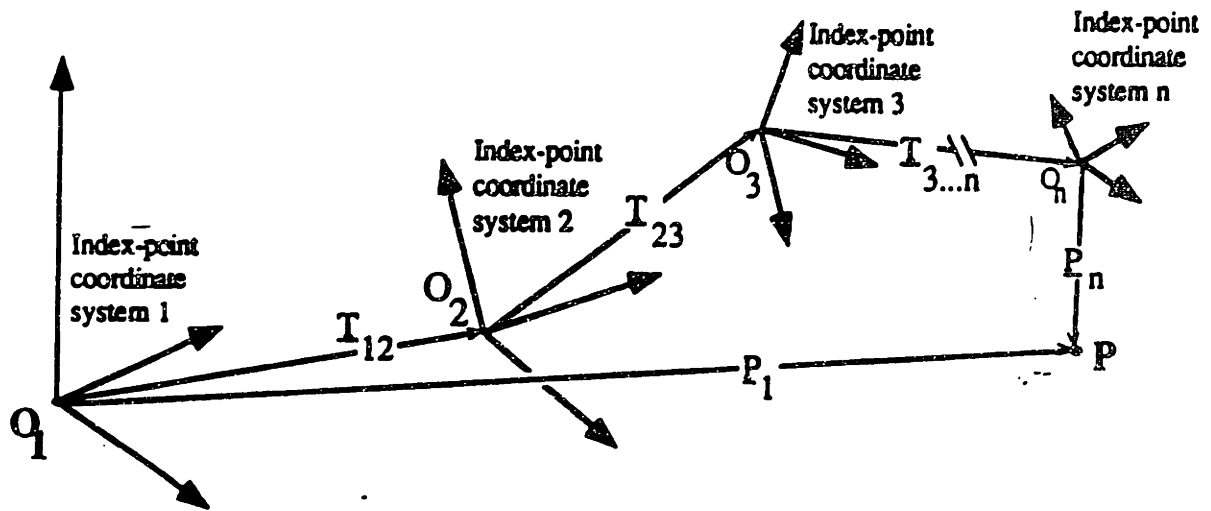


Figure A.2 The 3 consecutive rotations used to define the Euler angles  $\Phi$ ,  $\theta$ , and  $\Psi$



$$P_1 = T_{12} \cdot T_{23} \cdot \dots \cdot T_{3\dots n} \cdot P_n$$

**Figure A.3** The propagation of index-point coordinate systems. The local vector  $P_N$  can be represented in the global coordinate system  $O_1$  by the vector  $P_1$ . The vector  $P_1$  is the product of the transformation matrices of all the intermediate index-point coordinate systems multiplied by the local vector  $P_N$ .



**Appendix B: The statistical preassembly model**  
**Determination of a Transformation Matrix**

<b>Input Tolerances</b>		
Pattern:	0.0075	0.0025
Feature:	0.0030	0.0010
Thickness:	n/a	n/a
Perpend:	n/a	n/a
	(3 sigma)	(1 sigma)

**Note 1**

**Upper Hole Position (attach clip)**

x = 0.0000    0.0000  
y = 4.5000    4.5010  
z = 0.7300    0.7324  
          (nominal) (actual)

**Note 2**

**Lower Hole Position (attach clip)**

x = 0.0000    0.0000  
y = 2.5000    2.4997  
z = 5.4750    5.4740  
          (nominal) (actual)

**Note 3**

**Angular Orientation (rads)**

Phi = 0.0000    0.0000  
Theta = 0.0239    0.0004  
Psi = 0.0000    0.0000  
          (degrees) (radians)

**Note 4**

**Transformation Matrix (upper hole)**

1.0000	0.0000	0.0000	0.0000
0.0000	1.0000	-0.0004	4.5010
0.0000	0.0004	1.0000	0.7324
0.0000	0.0000	0.0000	1.0000

**Note 5**

**Transformation Matrix (lower hole)**

1.0000	0.0000	0.0000	0.0000
0.0000	1.0000	-0.0004	2.4997
0.0000	0.0004	1.0000	5.4740
0.0000	0.0000	0.0000	1.0000

**Note 1: Input tolerances**

The tolerance specifications for each part in the structure are the inputs to the statistical preassembly model. For this particular part of the aircraft floor (one of the floor beams), only the composite positional tolerances (pattern and feature location) for the pair of coordination holes is used. A more detailed description of composite positional tolerancing is given in Appendix C. The pattern tolerance selected was all (i.e., 3 sigma) coordination holes within a true position of .0075 inches from nominal locations. The feature tolerance was .003 inches, with the same caveats.

**Note 2: Determining the position of the upper hole**

The nominal positions for the holes (designer's intent) are entered in the left hand column of the next part of the model. Variability in the manufacturing process is simulated by determining the "actual" position of the coordination holes during a simulated build. The "actual" position is offset from nominal by a random value selected from a user-defined normal distribution with the parameters entered above. For example, the y axis position of the upper hole is nominally located 4.5000 inches from the y axis. In this particular simulation, the "actual" position is determined to be 4.5010 inches, or an offset of .001 inches. The offset between nominal and "actual" will be different for each subsequent run of the model.

**Note 3: Determining the position of the lower hole**

Uses the same methodology as was employed to determine the position of the upper hole. In this simulation, the "actual" position of the lower hole in relation to the y axis is 2.4997 inches, or .0003 inches less than nominal. Every offset is drawn independently from the user-defined normal distribution.

**Note 4: Determining the angular orientation of the holes**

This subsection of the model determines the Euler angles (described in detail in Appendix A) used in the transformation matrices. For this particular part, only the theta

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angle is non-zero (because we are dealing with rotations on the planar surface of the beam web). The theta angle is determined to be .0239 degrees off of nominal.

**Note 5: The transformation matrices for the upper and lower holes**

The transformation matrices for both holes are determined using the “actual” positions and Euler angles determined above (as described in Appendix A). These transformation matrices are then linked to the transformation matrices of downstream structures in the exact order of assembly, permitting the propagation of the simulated variability through the entire aircraft floor. The entire process can then be repeated using Monte Carlo techniques to gain a better understanding of the effects of detail part tolerances on the dimensions of the complete structure.



## **Appendix C: Summary of composite positional tolerancing** (Source: ANSI Standard Y14.5M-1982)

*Composite positional tolerancing.* Where design requirements permit the location of a pattern of features, as a group, to vary within a larger tolerance than the positional tolerance assigned to each feature in the pattern, composite positional tolerancing is used. Composite positional tolerancing specifies the location of feature patterns as well as the interrelation of features within these patterns. Requirements are annotated by the use of a composite feature control frame. Each horizontal entry in the feature control frame seen in Figure C.1 constitutes a separate requirement. The position symbol is entered once and is applicable to both horizontal entries.

*Pattern tolerance.* The upper entry is referred to as the pattern-locating control. It specifies the larger positional tolerance for the location of the pattern of features as a group. Applicable datums are specified in a desired order of precedence.

*Feature tolerance.* The lower entry is referred to as the feature-relating control. It specifies the smaller positional tolerance for each feature within the pattern (feature-to-feature relationship) and repeats the primary datum (same as the upper part of the frame). Each pattern of features is located from specified datums by basic dimensions. The lower entry, in addition to providing interrelationship control of the features in each pattern, controls the extent of attitude variation (perpendicularity in the case of Figure C.1) of each feature axis in relation to the plane established by Datum A. As can be seen from the sectional view of the tolerance zones in Figure C.2, the axes of both the large zones and small zones are parallel. The axes of the holes may vary obliquely (out of perpendicular) only within the confines of the respective smaller positional tolerance zones. The axes of the holes must lie within the larger tolerance zones and also within the smaller tolerance zones. In certain instances, a portion of the smaller zones may fall beyond the peripheries

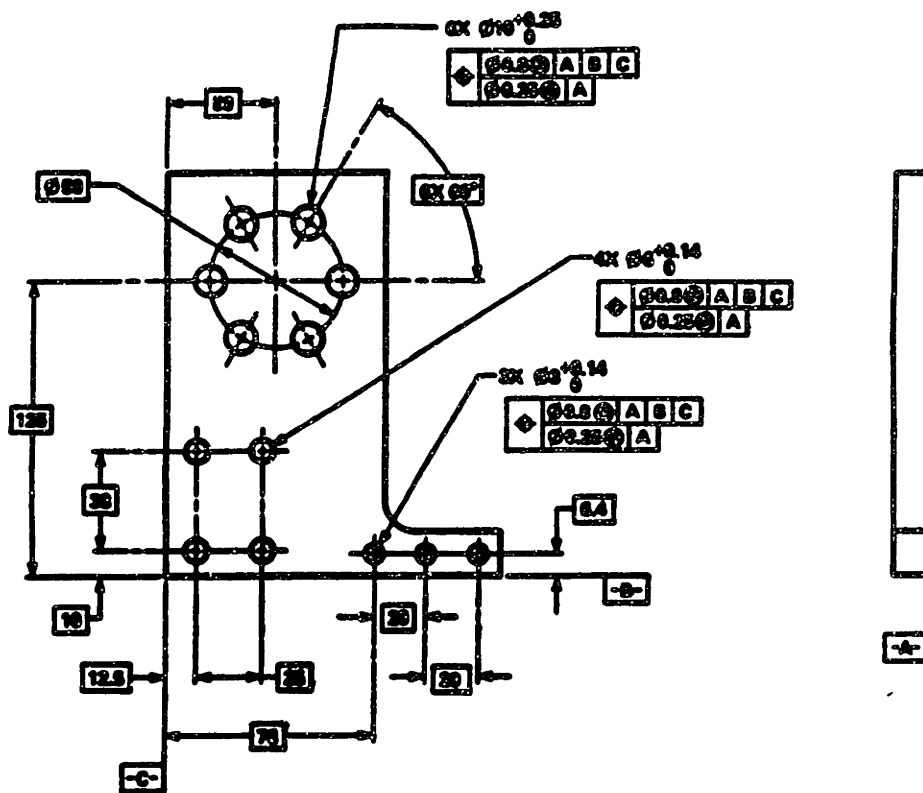


Figure C.1

Hole patterns located by composite positional tolerancing

of the larger tolerance zones. However, this portion of the smaller tolerance zone is not usable because the axis of the feature must not violate the larger tolerance zone.

**Bonus tolerance.** When a hole is at maximum material condition (minimum diameter), its axis must fall within a cylindrical tolerance zone whose axis is located at true position. The diameter of this zone is equal to the positional tolerance. This tolerance zone also defines the limits of variation in attitude of the axis of the hole in relation to the datum surface. It is only when the feature is at maximum material condition (MMC) that the specified positional tolerance applies.

Where the actual size of the feature is larger than MMC, additional or *bonus* positional tolerancing results. This increase of positional tolerance is equal to the difference between the specified maximum material limit and the actual size of the feature. The specified positional tolerance for a feature may be exceeded where the actual size is larger than MMC and still satisfy function and interchangeability requirements. In the case of the

holes at the bottom right side of the part shown in Figure C.1, a hole diameter of 3.10 inches would result in a *bonus tolerance* of position of .10 inches.

For additional information on composite positional tolerancing, please see ANSI Standard Y14.5M-1982.

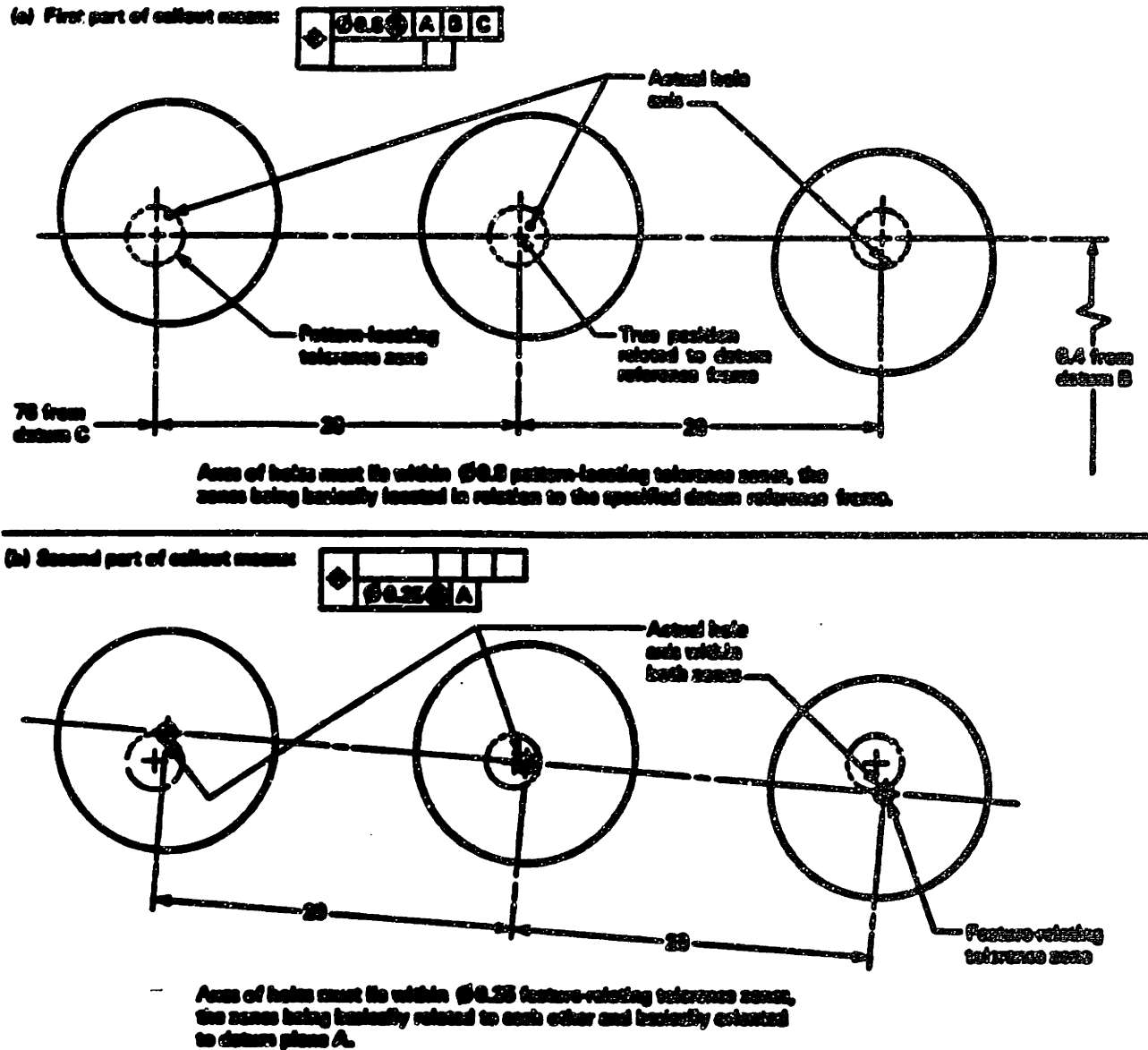


Figure C.2

Tolerance zones for three-hole pattern shown in Figure C.1