

**MODULE BASED CONFIGURATION DEFINITION TO ENABLE
DESIGN RE-USE AND MANUFACTURING SYSTEM
SIMPLIFICATION IN THE COMMERCIAL AIRCRAFT INDUSTRY**

by
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Submitted to the Departments of Aeronautics and Astronautics
and to the Sloan School of Management in Partial Fulfillment of
the Requirements for the Degrees of

MASTER OF SCIENCE IN AERONAUTICS AND ASTRONAUTICS
and
MASTER OF SCIENCE IN MANAGEMENT

at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
May 1995

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ABSTRACT

Boeing's current methods to define, control, and manufacture commercial aircraft are complex and labor intensive. Complex relationships between the functional specification, physical design, and production specification have created a production system which contains disconnected information flows. This situation limits the re-use of existing design resulting in extensive and unnecessary design customization. Extensive design customization pervades the manufacturing system. It has resulted in the creation of a complex manufacturing system which often introduces customer unique variability early in the production process and severely limits opportunities to capture economies of scale in production.

This research effort demonstrates a new methodology for configuration identification and control which enables re-use of existing design while simplifying the manufacturing system. At the heart of this methodology is a new data architecture. This architecture eliminates effectivity by aligning the functional configuration specification with the physical design and production configuration specifications. This alignment creates a library of re-useable product design and manufacturing processes which are configured directly from customer selected optional features.

The foundation of this new data architecture is the module. The module creates the relationships between the customer selected option and the parts, plans, and tools required to implement necessary activities on the factory floor. Advances in relational data base technologies allow the module to provide the sole authority definition for the product configuration. This definition is not limited to identification of the part number, but includes part location, surface finish, as well as other engineering and manufacturing data required to completely specify design and fabrication of the part or assembly.

Implementation of this new data architecture enables focused design activities to reduce cycle time and segregates production activities allowing implementation of a large scale synchronous production system.

Thesis Supervisors: Professor Eugene E. Covert, MIT School of Aerodynamics and Astronautics
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ACKNOWLEDGMENTS

The author gratefully acknowledges the support and resources made available to him through the Leaders of Manufacturing Program, a partnership between MIT and major U.S. manufacturing companies.

I would like to thank my advisors, Professors Eugene Covert and Steve Graves for their support and assistance throughout the internship. Their guidance and support is greatly appreciated. They helped me focus and explore very complex issues, but also let me develop the scope of this thesis.

I would also like to thank those employees at my internship site who took time to share their ideas, knowledge and time. In particular, I would like to thank Bob Hammer and Garnet Hizzey for creating the opportunity to conduct my thesis research in their organizations and especially for the fresh perspective they bring to our profession. Secondly, I would like to thank Gary Spies for his daily contribution and support. Lastly, I would like to thank the people on the DCAC program who provided me with the knowledge and information I needed to make this thesis complete, especially Carol Pittman, Peter Weertman, Paul Berg, Norm Carcas, Bruce Hiebert, Steve Haberman and Martin Bickeboeller. All of the people on the program helped deepen my understanding of design and manufacturing system from a business perspective.

Most of all, I would like to thank my wife, Michele, for her patience and support throughout this MIT adventure. It is an experience that we shall both look back upon with fond memories.

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1.0 INTRODUCTION

This thesis proposes a new methodology for identifying an aircraft configuration which enables the re-use of existing engineering design and simplification of the manufacturing system. The goal of the proposed methodology is to define a procedure to allow the production of commercial aircraft which are responsive to customer needs at significantly lower cost than is possible today. In section 1, a framework for this thesis will be described, beginning with an analysis of Boeing and the commercial aircraft industry. These analyses will provide a justification for research described in this thesis. Section 1 will provide a road map for the entire thesis.

1.1 Analysis of Boeing's Competition

The Boeing Company has dominated the commercial aircraft industry for the last three decades. Keys to Boeing's success have been attributed to several successful implementations of advanced technology, a family of aircraft able to meet customers diverse requirements, international production, and world class customer support. These factors have propelled Boeing to command the market with almost 60% share. However, strong international competition from Airbus is threatening Boeing's competitive position in the industry

Airbus Technology Investments Have Created A Family Of Outstanding Products -

Airbus has made a concerted effort to push technology in the commercial aircraft industry. These achievements include fourth generation aerodynamics, application of advanced composites in primary structure, two person cockpit, Category III automatic landing, automatic windshear protection, fly by wire digital flight control.¹ Airbus aircraft compete with Boeing in virtually every market segment except the 350+ seat segment. For example, the A320 competes directly with the 737-400. It offers a 9% advantage in cruise

¹ March, Atemis. The US Commercial Aircraft Industry and its Foreign Competitors, *The Working Papers of the MIT Commission on Industrial Productivity*, 2 vol. (Cambridge: MIT Press, 1989).

speed with an 8% reduction in total operating costs over the 737-400. These performance figures were one of the key contributing factors which led United's (a long time Boeing customer) selection of the A320 over the Boeing 737-400 in 1992². Product by product, Airbus offers aircraft which are technologically competitive with Boeing. (See Table 1.1)

Table 1.1 - Airbus Aircraft Competitive With Boeing.³

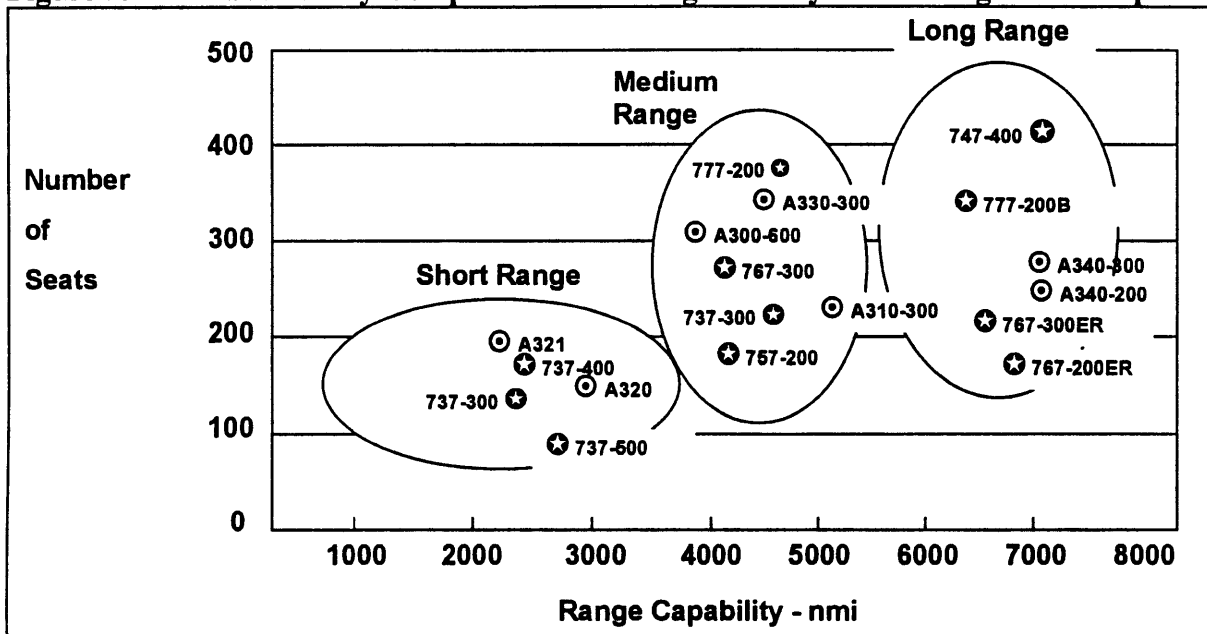
	737-400	A320-200	767-300	A310-300	747-400
Speed Airborne (Knots)	406	445	493	490	533
Direct Operating Cost Per Passenger Mile (\$/Person*Mile)	.026	.024	.026	.028	.026

Airbus Family of Aircraft Share Significant Design Commonality - Boeing was the first aircraft manufacturer to develop a family of aircraft which are able to satisfy a highly diverse set of airline requirements. Boeing's family of aircraft approach allowed airlines to achieve economies of scale in maintenance and training by capitalizing on aircraft commonality. In the last 15 years, Airbus has duplicated Boeings strategy and may even have improved upon it. Airbus has created a family of aircraft which competes directly with Boeing in virtually every market segment. (See Figure 1.1) In addition, Airbus has taken aircraft commonality to a new plateau. To extract maximum economies of scale in maintenance and training, Airbus has established unprecedented levels of design commonality throughout the family. Common design includes fuselage structure, flight deck, propulsion, wing, empennage and systems.

² Schmidt, Jennifer. Boeing Faces Competition From Airbus, National Public Radio, July 15, 1992.

³ Data derived from Air Transport Authority data, Air Transport Association Facts and Figures - 1994.

Figure 1.1 - Airbus Family Competes With Boeing In Every Market Segment Except 747.



Airbus Investing to Create World Class Customer Support - Boeing has been a leader in customer support for over 40 years. Boeing's documentation for AOG (aircraft on the ground) support is world class. Maintenance manuals, integrated parts catalogs, service bulletins allow excellent support for aircraft with immediate spares needs. This is an area that Airbus is lacking. However, Airbus recently announced that it will invest heavily into customer support operations in an effort to catch up to Boeing.

Boeing Aircraft Cost Too Much - The price of Boeing aircraft have increased significantly over the last 20 years. For example, over the last 20 years, the price of a 747 has gone from \$20 million in 1970 dollars to \$150 million in 1994 dollars while providing only 15% increase in available seating⁴. After adjusting for inflation, this represents an 82% increase over the cost of the original model. In a competitive environment where Boeing aircraft have clear performance benefits, these economic rents are justified. However, stiff competition will force Boeing to pursue more aggressive pricing policies.

⁴ Feldman, Joan. Just in time, not just in case: Boeing's push to reduce production costs, Air Transport World, April 1994.

1.2 Analysis of the Commercial Aircraft Industry

Deregulation Created a Highly Competitive Environment for Boeing's Customers - The Civil Aeronautics Board (CAB) was formed in 1938 to promote air transportation. The CAB accomplished these objectives by regulating both fares and route structures. These actions resulted in performance and technology based competition among the airlines.⁵ In 1978 the airlines deregulated. This factor as well as international competition and the internationalization of production have moved the industry from a technology based American oligopoly and toward a laissez-faire, competitive, cost based, global market.

Changes in the underlying economics in Airline Industry can be seen by analyzing airline industry data. Table 1.2 summarizes airline industry data from 1970 through 1993. From 1970 to 1985 the number of carriers have tripled while total revenue per passenger seat mile has fallen to half of pre- deregulated levels. These changes placed severe competitive pressure on the air carriers. From 1985 to present, the industry has consolidated with little impact on passenger load factors or total revenue per passenger mile.

Table 1.2 - United States Airline Industry Data⁶

	1970	1975	1980	1985	1990	1992	1993
Number Of Carriers	39	33	63	95	60	-	-
Passenger Load Factor (%)	50	54	59	61	62	64	64
Revenue Per Seat Mile (1975\$)	0.095	0.077	0.074	0.051	0.046	0.042	0.043

⁵ March, Atemis. The US Commercial Aircraft Industry and its Foreign Competitors, *The Working Papers of the MIT Commission on Industrial Productivity*, 2 vol. (Cambridge: MIT Press, 1989).

⁶ Pindyck, R.S. and D. L. Rubinfeld, Microeconomics, Second Edition, 1992, and Air Transport Association. The Annual Report of the US Scheduled Airline Industry, 1994

Airlines are Focusing on Cost Control - The competitive nature of the industry has put air carriers in the red. After four years of record losses⁷ totaling over \$13 billion⁸, airlines are cutting costs and streamlining operations. Airlines are reducing their direct as well as their indirect costs. Although indirect costs are an important factor which comprise almost half of the airlines total cost, aircraft manufacturers influence direct operating costs. Direct operating costs include fuel costs, maintenance expenses, crew wages and aircraft ownership. For new aircraft to be attractive to air carriers, they must sustain competitive levels of performance while reducing direct operating expenses. Technology which, in the past, was supported by regulated fares must now earn its way onto the aircraft. With competition constraining growth in airfares, future economic gains will be achieved through net reductions in operating expenses.

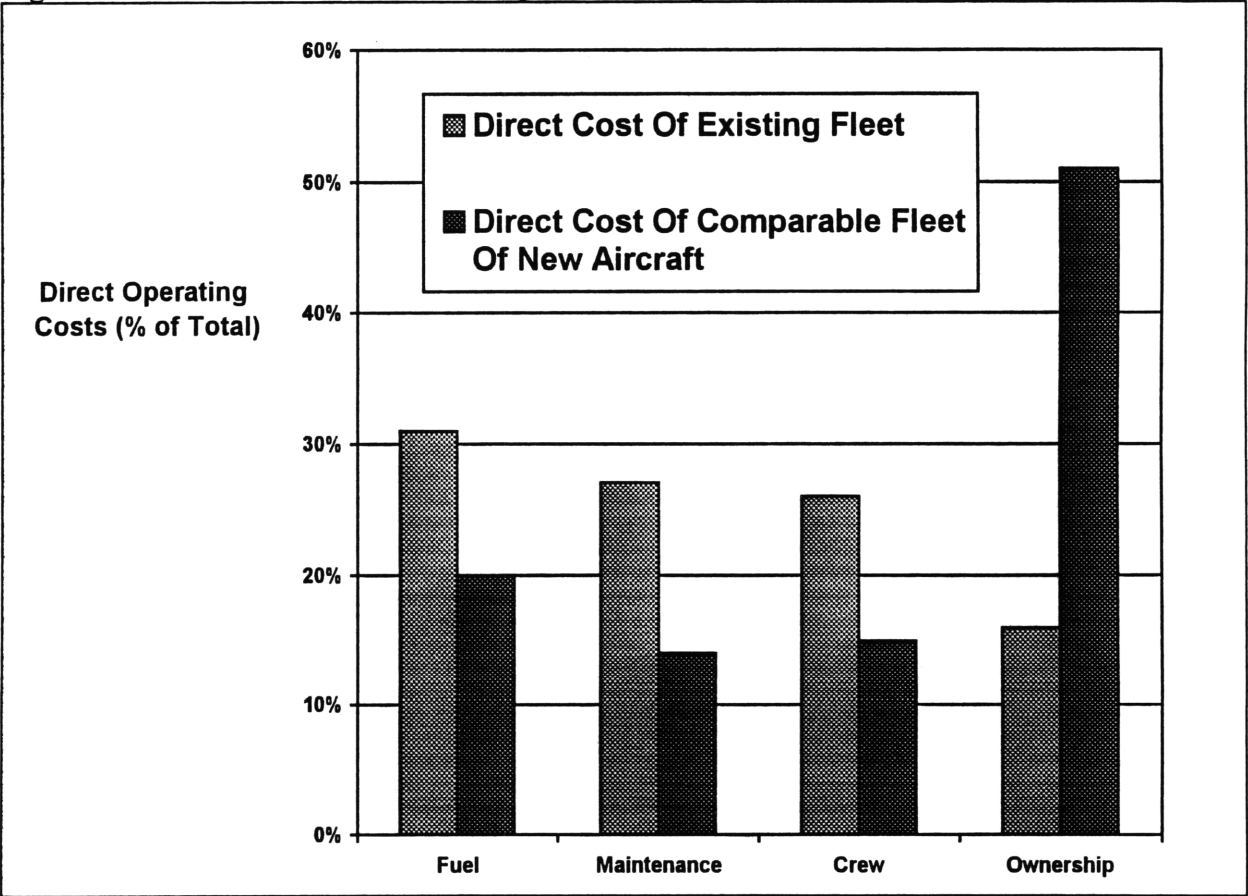
Direct Costs For New Aircraft Are Now Dominated By Aircraft Ownership - Direct operating expenses fall into four basic categories: Fuel, maintenance, crew and aircraft ownership. Over the last 30 years, advances in aerospace technologies have reduced fuel, maintenance and crew costs. However, these same technologies have significantly increased the cost of aircraft ownership. Ownership costs have become a dominating expenditure for the airlines. Cost of ownership represents the annual depreciation of the aircraft asset plus the opportunity cost of capital. Ownership costs for aircraft that are purchased and owned by the airline include the annual depreciation write-off as well the cost of debt. Ownership costs for leased aircraft include the annualized lease expense. Figure 1.3 compares direct operating expenses for the existing aircraft fleet to a new fleet of similar composition. Although advances in technology have reduced fuel consumption, maintenance expenditures and crew costs, **cost of ownership** has significantly increased. Cost of ownership for new aircraft represents approximately 54% of the total direct operating costs born by the airlines. This can be contrasted by the cost of ownership of the existing fleet which is currently 15% of direct operating expenses. High cost of ownership makes the older, depreciated assets relatively attractive for airlines.

⁷ Betts, Paul. Survey of Aerospace, The Financial Times Limited, September 2, 1994.

⁸ Green, Ronald, Aerospace: Industry Overview, U.S. Department of Commerce-U.S. Industrial Outlook, January, 1994.

Today, Boeing is facing a new competitive environment. These threats arise from a new and highly capable international competitor as well as the potential for airlines to refurbish older, depreciated aircraft. High cost of ownership is preventing airlines from acquiring new, technologically superior aircraft. To succeed in the future, Boeing must reduce the cost of ownership of new commercial aircraft. This will require major reductions in the cost of designing and manufacturing aircraft. To achieve these significant cost reductions, Boeing must fundamentally re-think the way it configures and manufactures aircraft.

Figure 1.3 - Cost of Aircraft Ownership Dominating Airline Direct Costs⁹



⁹ Data derived from Air Transport Authority, Air Transport Association Facts and Figures - 1994.

Today, Boeing is facing a new competitive environment. An environment which requires major reductions in the cost of manufacturing aircraft. To achieve significant cost reductions, Boeing must fundamentally re-think the way it configures and manufactures aircraft

1.3 Goal of the Research Project

The goal of this research project was to develop an aircraft configuration identification and control process which enables maximum re-use of existing design while simplifying the manufacturing system. This research project focuses on the development and documentation of an advanced configuration control process and corresponding data architecture (including its application to typical aerospace structure). In addition, this project investigates data conversion requirements thereby creating a linkage from the “As-Is” world of custom design and one-of-a-kind manufacture to the “To-Be” world of design re-use and tailored manufacturing systems making maximum use of economies of scale in both design and manufacture.

The research was conducted inside the Define and Control Airplane Configuration (DCAC) Program within the Boeing Commercial Aircraft Group. Research activities spanned a seven month period beginning June of 1994.

1.4 Structure of the thesis

Section 2.0 of this thesis will describe Boeing’s current methods for defining and implementing new aircraft. This section will describe the complexity of existing processes, and introduce a concept called “Effectivity”. Section 3 will evaluate current processes in terms of labor intensity, flow time, design re-use, and economies of scale. Section 4 will describe a new configuration process and its related data architecture. This section will explicitly show how this new process and data architecture re-uses existing design, maximizes economies of scale in production and simplifies the manufacturing system. Section 5 will apply this new methodology to complex aircraft structure to demonstrate

proof of concept. Section 6 will describe, in detail, the impact of the new product architecture on the engineering drawing system. This section will describe the engineering drawing structure, demonstrate how alternate views are created, show how these views enable critical initiatives such as Hardware Variability Control, and introduce a new concept called a “parametric installation”. Section 7 will address the data conversion issue and show concrete examples of how effectivity is removed from the product structure while converting existing data into the new product architecture. Section 7 will also describe the necessary configuration rules and how these rules are implemented in this new system. Section 8 will describe the opportunity for synchronous production and the role of manufacturing system analysis and modeling. Finally, this thesis will conclude with a summary of the research findings and make recommendations for future development.

2.0 DESCRIPTION OF CURRENT PROCESSES

Today, Boeing executes an aircraft customization process for every aircraft delivered. This process tailors previously designed aircraft to exactly fit the customer's wishes. In this section, processes and data related to this customization process are described. The process model begins with initial customer contact and ends with delivery of a certified aircraft. The overall process is summarized by a process flow diagram shown in Figure 2.1. The following describes each of the processes, data flows, and organizations required to create the transactions.

Negotiate & Sell Airplane - Negotiate and Sell Airplane represents the beginning of the process and includes Boeing's first contact with a potential customer. Sales personnel conduct discussions to determine customer needs. Discussions emphasize tailoring potential aircraft to meet specific route requirements, maximizing aircraft revenue potential, and creating interior layouts which provide passenger appeal. Upon completion of the initial contact, the sales organization launches a formal internal assessment of the customer's needs under the marketing organization.

The Marketing organization provides internal analyses of the customer needs and formulates a set of aircraft solutions. These analyses include financial, operational impact, operating cost, and revenue sensitivity studies. In addition, assessments of the competitors fleet are studied in an effort to conduct comparison analysis. Upon completion of the marketing study, the Sales organization conducts a series of discussions with the customer to solidify market opportunities.

At this point in the negotiation, the customer usually requests a formal proposal from Boeing. This proposal documents the Boeing solution to the customers problem. It includes the type and number of airplanes as well as timing for deliveries.

Figure 2.1- Typical Customer Introduction Process

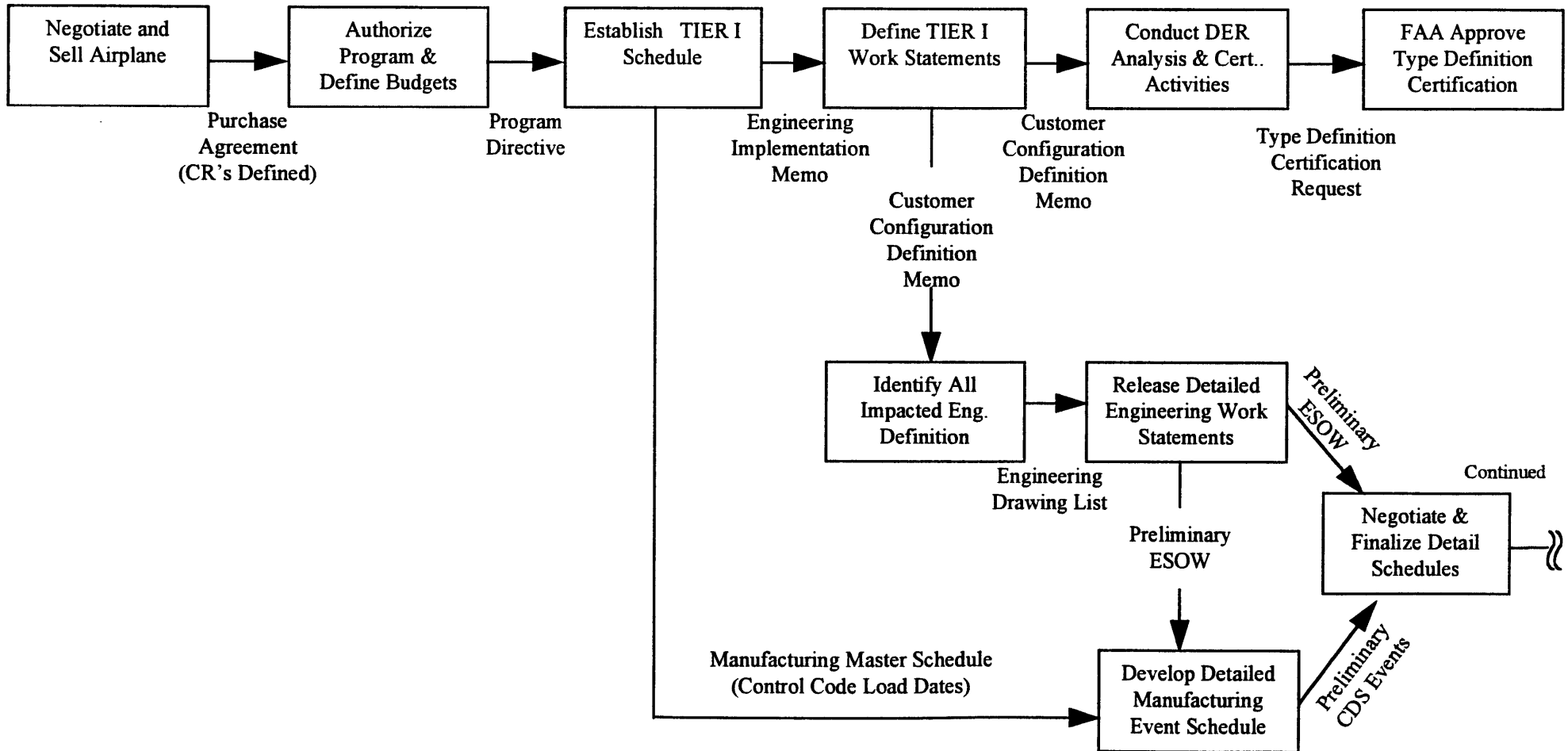
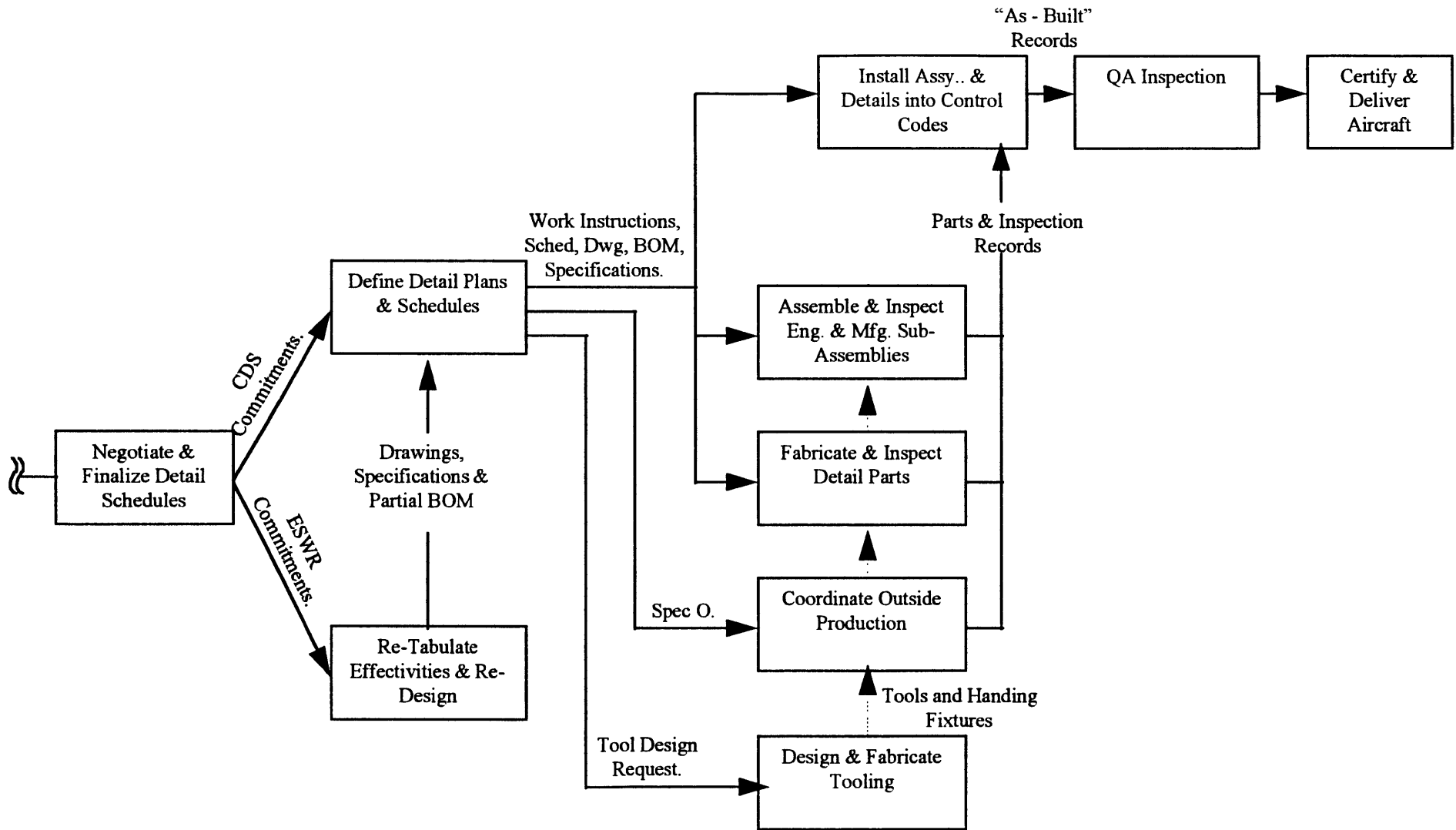


Figure 2.1- Typical Customer Introduction Process (Cont)



The formal proposal is prepared by the Sales, Customer Engineering, Finance, Pricing, Treasury organizations. After the proposal is complete, Contracts submits the proposal to the customer.

Upon customer acceptance of the proposal, Customer Engineering conducts a series of discussions to define the details of proposed configuration. These discussions focus on the detail definition of specific optional features. These features are usually selected from the "Configuration Specification". This specification describes not only the basic configuration of the aircraft, but all currently available and supported optional features. A typical change request contained in the Configuration Specification is shown in Figure 2.2.

Figure 2.2 - Typical Change Request From The Configuration Specification¹⁰

3246CG5002	CARBON BRAKES TEMPERATURE INDICATING SYSTEM
	MEW = +20 lbs OEW = +20 LBS
	Alternate To: 3246CG5001
<p>Install a main landing gear brake temperature indicating system for carbon brakes. Brake temperature indication for each main landing gear brake shall be provided in the flight compartment. A high brake temperature condition shall be annunciated by a light located on the center main instrument panel.</p> <p>A temperature sensor shall be installed in each main landing gear brake. A monitoring unit shall be located in the main E/E equipment rack. Temperature indication shall be provided by the Engine Indicating and Crew Altering System (EICAS).</p>	

If existing optional features contained in the Configuration Specification do not satisfy customer needs, engineering change proposals are developed and distributed to Design Engineering, Sales, and Contracts. Each organization analyzes the change proposal to determine technical feasibility, pricing and offerability.

¹⁰ Renton Division Customer Engineering, Configuration Specification Model 757-200 Revision G, Document Number. D924N104, The Boeing Company, December 15, 1993.

If accepted by Engineering, Sales and Contracts, new engineering changes are officially offered to the customer and recorded in the Customer Specification. After the Customer Detail Specification is complete, a purchase agreement is created and the aircraft is officially ordered.

Authorize Program & Define Budgets - After completion of the Purchase Agreement, the Program Management Organization creates and distributes a Program Directive. This memorandum officially authorizes all activities required to deliver the specified airplane. It defines the target delivery date, the revision level of the Detail Specification, and the effectivity¹¹ tabulation block for the particular customer.

Establish Tier I Schedule - Upon receipt of the Program Directive, the Engineering Operations organization releases a Engineering Implementation Memorandum which defines the official customer designator, manufacturing master schedule, aircraft line number. The Engineering Implementation Memorandum also established schedule control for key engineering events. These events include, but are not limited to, (1) completion of Buyer Furnished Equipment (BFE) and Seller Furnished Equipment (SFE) lists, (2) release of Purchased Outside Production (POP) document, (3) completion of the Layout Of Passenger Accommodations (LOPA), (4) release of Final Assembly and Top Collector Drawings, (5) presentation of interior color and decor to customer, (6) release of interior finish specification. These major events form the basis of the Tier I schedule.

Define TIER I Work Statements - Customer Engineering releases the basic engineering work statement. This work statement is called the Customer Configuration Definition Memo. The Customer Configuration Definition Memo describes the customer features

¹¹ Effectivity tabulation block is a series of code numbers that identify all aircraft, within a basic model, that belong to a particular customer. These code numbers are applied to the drawings as a method for defining the aircraft configuration.

defined in the purchase agreement at a level of functionality and specificity similar to the change request shown in Figure 2.2.

Conduct DER Analysis & Certification Activities - Based on the Customer Configuration Definition Memo, Designated Engineering Representatives (DER's) audit the proposed configuration for significant differences from the last certified airplane in an effort to uncover potential certification anomalies. The DER's then propose a certification plan for the new airplane. The certification plan is sent to the Regulatory Agency for approval. Upon Regulatory Agency approval, the Engineering organization performs certification activities and reviews the results with the Regulatory Agency as required.

FAA Approve Type Definition Certificate - After certification activities are complete, the Regulatory Agency Certifies the Design Change Request. After all Design Changes have been approved for a particular aircraft, the Regulatory Agency grants "Type Definition" certification.

Identify All Impacted Engineering Definition - Concurrent to DER analysis, Design Engineering updates Buyer Furnished Equipment (BFE) and Seller Furnished Equipment (SFE) lists. However, the majority of Design Engineering's effort is spent updating internal design data to reflect the functional requirements specified in the Customer Configuration Definition memo. Change Requests (extracted from the Customer Configuration Definition memo) are distributed to each of the engineering organizations. Lead engineers in each functional organization determine the impact of the proposed change on the engineering drawings. It should be noted that this is a very informal process which relies heavily on the expertise of each lead engineer.

Release Detail Engineering Work Statements - Lead engineers write work statements for each engineering drawings impacted by the relevant Change Requests. These work statements detail all changes to the engineering drawings. These changes may impact the drawing picture sheets, parts lists or process specifications. Along with work statement

definitions, preliminary schedules are developed which describe the dates at which engineering definitions will be ready to support manufacturing activities.

Develop Manufacturing Events Schedule - Manufacturing Engineering organization proposes a detailed build sequence for the aircraft. This information is then used by Industrial Engineering organization to match proposed build sequences with work center needs dates. (Work center need dates, often referred to as Control Code Load dates, represents dates which major assemblies are to be moved into and out of a particular work centers as defined in the manufacturing master schedule.) Detailed part need dates for each work center are then recorded in the Commitment Development Schedule (CDS) schedule tracking system.

Negotiate and Finalize Detail Schedules - Representatives from Engineering and Manufacturing organizations finalize schedule commitments through a series of coordination meetings. In these meetings, engineering drawing availability dates are compared to manufacturing need dates to identify schedule anomalies. When engineering drawing availability dates do not satisfy manufacturing requirements, alternative courses of action are studied. These actions might include moving work packages to down stream work centers thereby postponing the need date for the engineering data, or increasing engineering manpower thereby making the engineering available at an earlier date. Upon completion of the negotiation, committed engineering and manufacturing schedules are loaded into computerized schedule tracking systems. The Engineering system is called Engineering Schedule Work Report (ESWR) while the manufacturing system is called Commitment Development Schedule (CDS) System.

Re-Tabulate Effectivities & Re-Design - The engineering organization commences design activities as committed in the ESWR. This job entails (1) designing new hardware to satisfy new customer requirements (2) updating effectivity inside the engineering parts lists and on the engineering drawing. It is useful to think of effectivity as a process similar to putting the customer's name on every drawing that is used to build his airplane. (It should

be noted that maintaining the Effectivity system is a labor intensive job and will be discussed at great length in section 3.)

Define Detail Plans and Schedules - The entire manufacturing system is coordinated through a series of plans and schedules and work instructions. The Inventory Management and Manufacturing Engineering organizations define the build sequence and schedule for each and every part that is to go onto the aircraft. Inventory Management Organization (IMO) initiates activities by applying manufacturing related information to each part shown in the Engineering Bill of Material. Manufacturing information specifies the work center that consumes the part and whether the part is purchased from an outside supplier or made internally. Manufacturing Engineering receives the part data from IMO and (1) completes definition of the Bill Of Materials by identifying fastener and standard part requirements, (2) defines the build sequence, (3) specifies potential tooling requirements, (4) develops work instructions for the factory floor. Prior to release of the work instruction, Industrial Engineering collects this data and conducts time and motion studies to assess time requirements for each job in the work instruction. When these studies are complete, work instructions (jobs) are scheduled and released through the Manufacturing & Assembly Installation Data System (MAIDS) to the factory.

Design & Fabricate Tooling - The Tooling organization receives Tool Design Request (TDR) from Manufacturing Engineering to support the “As-Planned” build sequence. Tooling responds by designing and fabricating the required tool in compliance with the Commitment Development Schedule.

Coordinate Outside Production - Upon completion of detail plans and schedules, Manufacturing Engineering releases manufacturing requirements (engineering drawings, part lists data, inspection requirements, process specification references, schedule requirements, etc.) in a document called a “Spec O” to the Material organization. The Material organization defines a contract with an outside supplier incorporating key requirements contained in the “Spec O”. Finally, outside suppliers fabricate and deliver

hardware per the contractual requirements to the point of use specified in the manufacturing sequence.

Fabricate and Inspect Detail Parts - The fabrication division receives work instructions, schedule requirements (CDS events), engineering drawings and the manufacturing enhanced Bill of Material and fabricates the detail parts. Fabrication activities follow the work instructions contained in detail part plans. When complete, parts are inspected per the engineering drawing and transported per the Manufacturing Engineering plan to the appropriate assembly area.

Assemble and Inspect Engineering and Manufacturing Sub-Assemblies - Work centers responsible for sub-assembly collect detail parts from the fabrication centers. Parts are either immediately consumed by an assembly or are held in inventory for later use. Assembly Effectivity Controlled (AEC) plans are the basis for the build procedure in assembly areas. Assemblies can be part number controlled (similar to detail part fabrication) or effectivity controlled. Effectivity controlled parts are given synthetic part numbers and are inspected per the manufacturing part accountability specified in the AEC plan. After an assembly is complete, it is transported per the Manufacturing Engineering plan to the appropriate installation work center (Control Code).

Install Assemblies and Details Into Control Codes - Physical locations on the factory floor which conduct final assembly operations are commonly referred to as control codes. Detail parts and sub-assemblies are consumed in the control codes via work instructions contained in the Operations and Inspection Record (O&IR) plan. Parts are installed using the plan and are inspected per the installation drawing. Effectivity controls the configuration as it is recorded in the drawing parts list as well as on the picture sheet. In O&IR driven work centers, installation activities are not part number inspected. They are inspected via inspection events explicitly defined in the O&IR plan. These events may verify that a process has been successfully completed, an assembly has been properly installed, or that the entire O&IR plan has been successfully implemented.

Quality Insurance Inspection - After all work instructions and inspection events have been completed, O&IR plans are submitted to the quality assurance organization. These completed plans becomes the “As-Built” records for the aircraft. The “As-Built” records define the condition of the aircraft upon delivery. “As-Built” records are recorded in computer database called the Automated Configuration Accounting System (ACAS). Quality Assurance then uses this database to verify that all of the O&IR plans which were suppose to be implemented on an airplane for a particular effectivity, have been implemented. As-Built records are then stored in a vault for future reference.

Certify and Deliver Aircraft - Upon completion of build sequence and verification of the “As-Built” records, the aircraft is granted an air worthiness certificate by the Quality Assurance organization. Contracts is now able to deliver the airplane to the intended customer.

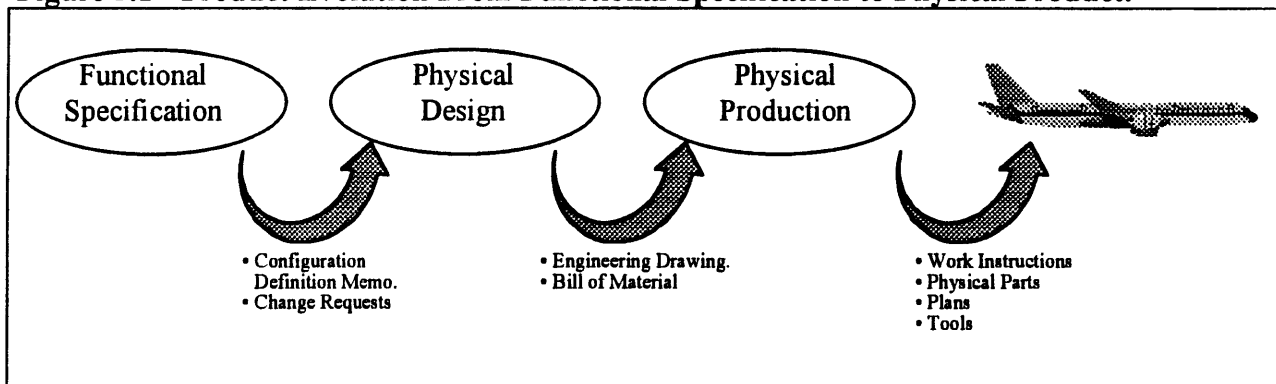
3.0 CRITICAL EVALUATION OF THE CURRENT PROCESS

Today's process is complex and labor intensive. A key source of complexity is related to configuration specification of the product. Configuration of the product is specified in three distinctly different and very important ways. These are (1) functional specification, (2) physical design specification (3) and physical production specification. The transformation of configuration specification across these domains is a fundamental weakness in Boeing's existing process. This section will document this weakness and show its negative effect on the design and manufacturing system. This section will conclude with the key argument of this thesis: accurate, consistent, and re-usable configuration specification across the enterprise enables significant cost reduction in both engineering and manufacturing activities.

3.1 Configuration Specification Across the Enterprise is Disconnected

The major source of complexity in the existing process arises from transforming specification of the functional configuration into the design and physical production system. Products evolve from a functional specification (as defined in the purchase agreement/customer configuration definition memo) to a physical design (as described in the engineering drawings) to a physical production definition (as described in a series of work instructions) into a finished aircraft. (See Figure 3.1).

Figure 3.1 - Product Evolution From Functional Specification to Physical Product.



The relationships between these three distinct configuration specifications are naturally complex. However, Boeing's effectivity based design process significantly increases the complexity of an already complex process. Increased complexity means increased labor requirements, higher error rates and increased costs of manufacture. Order of magnitude estimates suggest that 25%-35% of the Design Engineering and Manufacturing Engineering workforce are dedicated to maintaining effectivity codes on engineering drawings and fabrication/assembly plans.

3.2 Effectivity Based Configuration Specification Is Labor Intensive and Complex

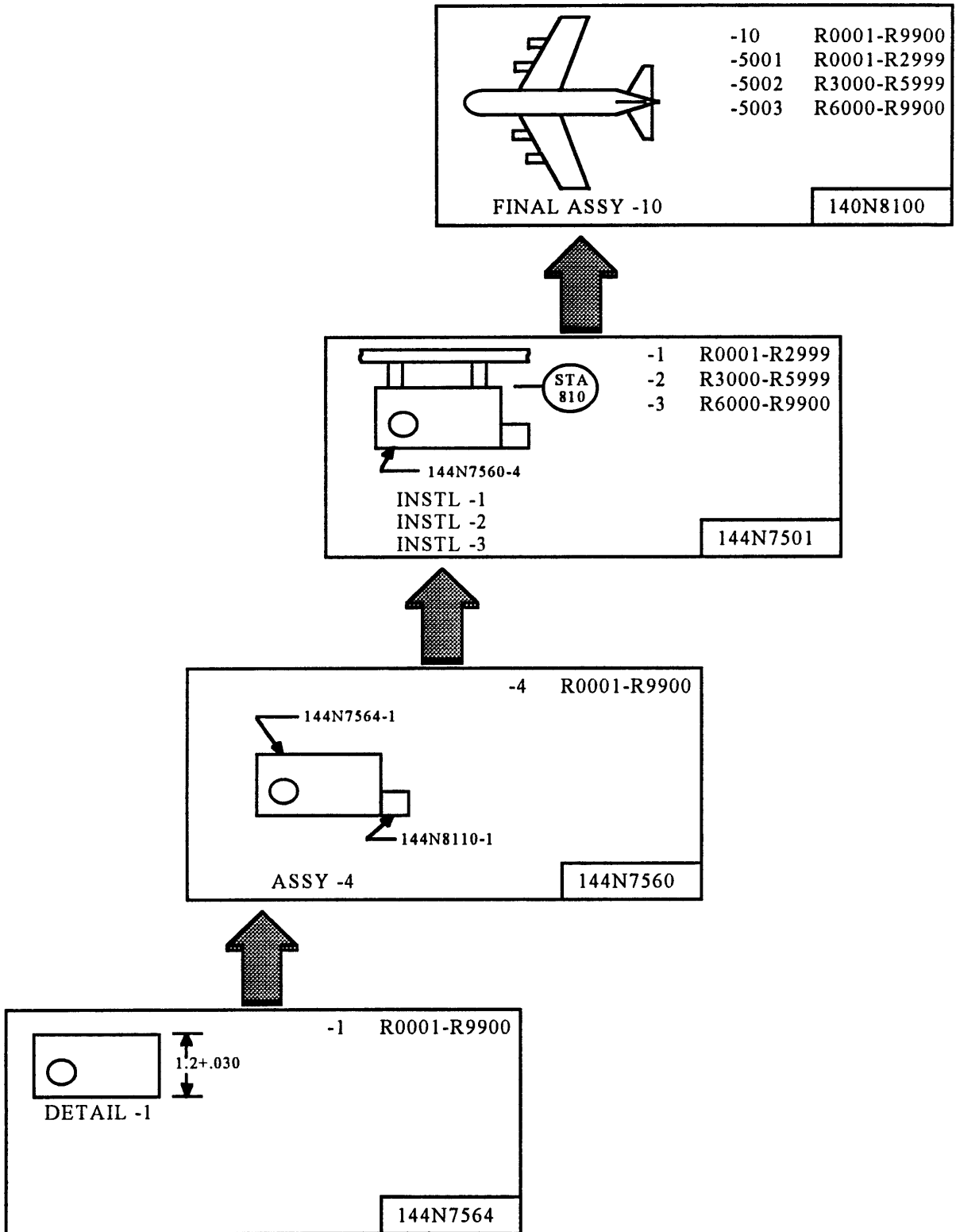
Boeing's effectivity based system for controlling the configuration specification of aircraft was first used on military aircraft in the early 1940's. This system specifies the aircraft configuration by assigning a customer specific identification number on each engineering drawing. This allowed the drawings themselves to describe which airplanes the parts described by that drawing are used on. This system is analogous to ordering a car at the automobile dealership and having the automobile manufacturer place your name on every engineering drawing used to define and fabricate that particular car.

The best way to understand effectivity is to work through a particular example. Consider a typical Boeing aircraft which is defined through the series of stylized engineering drawings shown in Figure 3.2. These drawings are organized hierarchically starting with a final assembly drawing (140N8100) which collects all of the appropriate major and minor assemblies and ends with a detail part drawing (144N7564) which describes all of the design features found on a single detail¹².

The Final Assembly drawing identifies all major and minor assemblies required to build a specific configuration of the aircraft. In Figure 3.2, the 140N8100 Final Assembly drawing identifies four possible configurations of the aircraft. The basic aircraft is specified by the 140N8100-10 configuration. The passenger version of the aircraft is

¹² Detail is used in the engineering design context as single parts used to create assemblies.

Figure 3.2 - Simple Effectivity Example



specified by the 140N8100-5001 configuration. The cargo version of the aircraft is specified by the 140N8100-5002 configuration. The high gross weight version of the aircraft is specified by the 140N8100-5003 configuration. Figure 3.2 also shows strings of numbers located on the Final Assembly drawing next to the -5001, -5002, and -5003 configuration identifiers. These strings are commonly referred to as customer effectivity codes. Unique effectivity codes are assigned to each customer and are used to determine which customers received the -5001, -5002, or -5003 versions of the aircraft. Each effectivity represents a unique customer. For example, R0001, R0002 and R0003 are aircraft which were delivered to United Airlines. R0004 is an aircraft which was delivered to Delta Airlines. United Parcel Service took delivery of eight aircraft represented by effectivity codes R3000 through R3007. This process uses a code number to record the name of the customer on the engineering drawing for configuration identification and tracking purposes. Figure 3.2 shows that the R3001 airplane was built to the -5002 cargo configuration..

The 140N8100 drawing defines the final assembly configuration of the aircraft. However, the configuration of the assemblies as they were installed on the aircraft are shown in the next drawing down in the drawing hierarchy. The 144N7501 installation drawing shows the configurations of the 144N7560-4 assembly as it is installed in the aircraft. The 144N7501-1 installation contains peculiarities that are unique to the passenger version of the aircraft.¹³ Effectivity codes limit the use of the 144N7560-1 configuration to the passenger aircraft only. Likewise the 144N7560-2 installation is used only on the cargo version of the aircraft and the 144N7560-3 installation is used only on the high gross weight version of the aircraft.

Below the 144N7501 installation drawing is the 144N7560-4 assembly. This assembly is common to all versions of the aircraft as is seen by the effectivity codes (R0001-R9900). Finally feeding the 144N7560-4 assembly is the 144N7564-1 detail part. The detail part

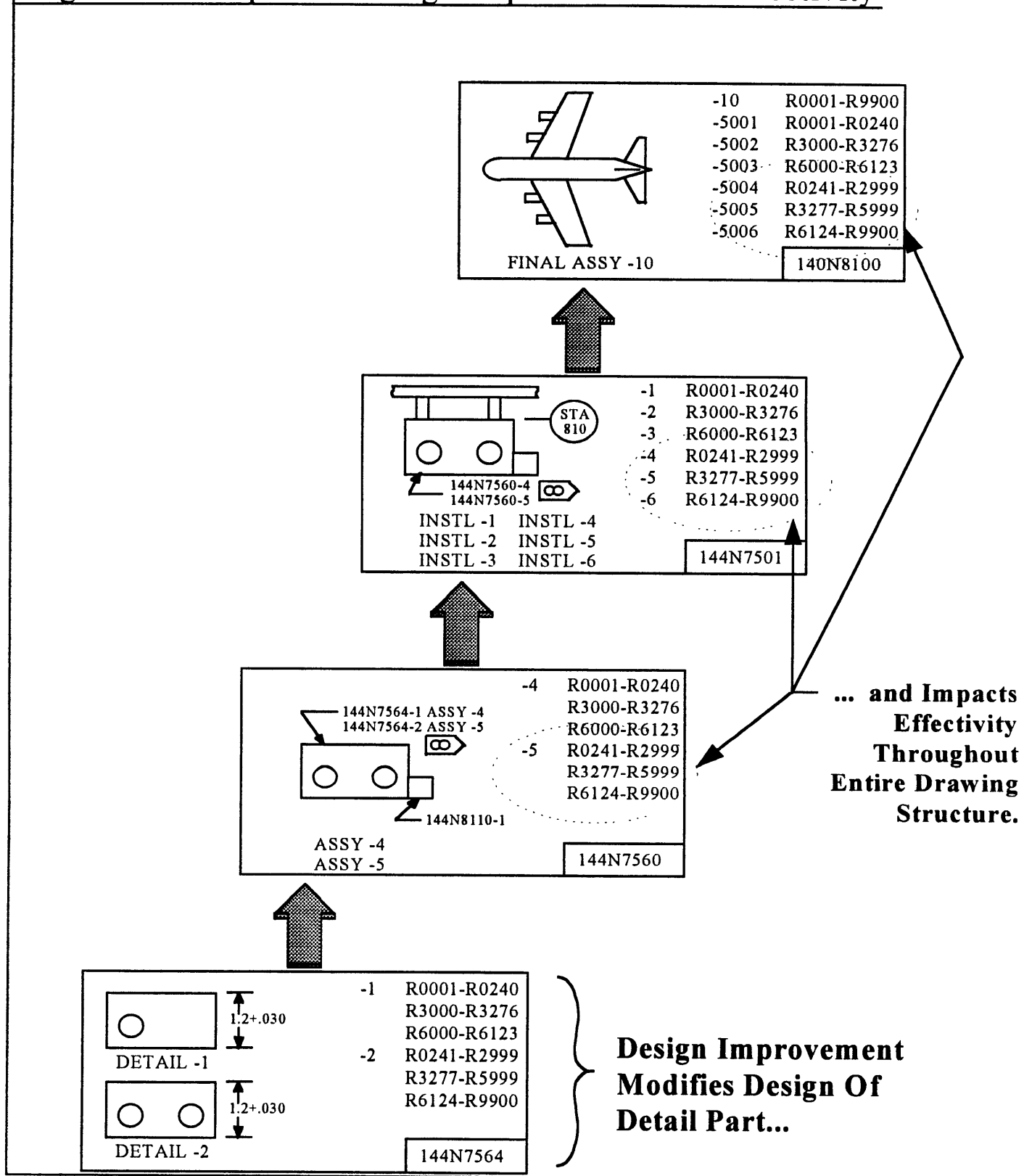
¹³ Assume the design peculiarities are related to installation processes and are not apparent on the picture sheet.

also is used on all versions of the aircraft. These 4 levels of drawing together define the engineering definition of the aircraft.

At first blush, effectivity seems quite logical and relatively simple. However, consider the impact of a design change on this type of configuration identification system. Assume that a design modification alters the design of the 144N7564-1 detail part by incorporating a second hole in the body of the part as is shown in Figure 3.2. Because the parts engineering definition has changed, it is re-identified as the 144N7564-2 detail part. Effectivity codes must now be altered to accurately reflect which airplanes received the 144N7564-1 detail part versus which airplanes received the 144N7564-2 detail part. To record this change on the detail part drawing, the effectivity codes are modified from a single block (R001 to R9900) to six unique blocks of code numbers (R0001 to R0240, R0241 to R2999, R3000 to R3276, R3277-R5999, R6000 to R6123, R6124 to R9900) as is shown in Figure 3.3.

These six blocks were created to track the three versions of the aircraft which had been delivered with the 144N7564-1 detail versus the three versions of the aircraft which received the 144N7564-2 detail part. The effectivity codes shown in Figure 3.3 show that airplanes R0001 through R0240 of the passenger version of the aircraft contain the 144N5764-1 detail part. Likewise, cargo aircraft R3000 through R3276 received the 144N5764-1 detail part and the high gross weight aircraft R6000 through R6123 received the 144N5764-1 detail part. In addition, Figure 3.3 also shows that airplanes R0241 through R2999 of the passenger version of the aircraft have, or will receive, the 144N5764-2 detail part. Likewise, cargo aircraft R33277 through R5999 have, or will receive the 144N5764-2 detail part and the high gross weight aircraft R6124 through R9900 have or will receive the 144N5764-2 detail part. Modifications to effectivity codes are required on each drawing. The total impact on the effectivity codes is shown in Figure 3.3. Not only was effectivity of the detail part modified, but effectivity throughout the drawing structure has been impacted. As is demonstrated in this example, small changes

Figure 3.3 - Impact of Design Improvement On Effectivity



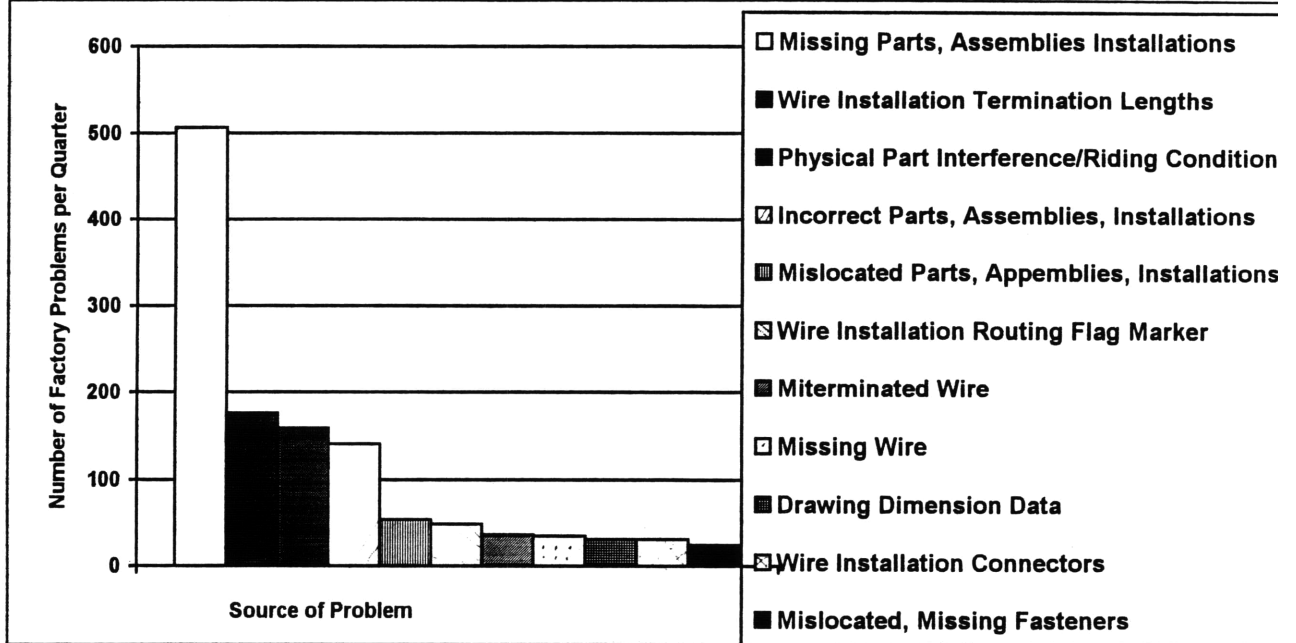
in design result in very large changes to effectivity tabulation throughout the entire drawing structure. Since this information is maintained manually on the drawing picture sheet, design modifications represent significant complexity, effort and labor cost simply to maintain the effectivity codes on all of the drawings.

The effectivity example described in Figures 3.2 and 3.3 was made relatively simple because only three versions of the aircraft were considered. Since only three version of the aircraft were considered, only three separate effectivity blocks were originally required. In reality, Boeing maintains a separate effectivity block not only for each model but for each customer as well. Today, hundreds of effectivity blocks are used to define the aircraft configuration. Each effectivity requires the effectivity tabulation procedure demonstrated in the previous example every time a design change is incorporated.

After analyzing the basic procedure for managing the aircraft configuration with effectivity, it is easy to see how typical design changes require only 25% of the total effort to “engineer the change” and 75% of the effort to maintain effectivity on the engineering drawings.

Configuration specification using effectivity codes is complex and leads to errors. Incorrect specification of the configuration results in problems in the factory. In fact, problem reports collected in the factory for the 4th quarter of 1994 are shown in Figure 3.4. This data shows that over 50% of the problems which were attributed to the engineering organization were a direct result of improper specification of the configuration. This is three times the number of problems which resulted from physical part interferences. The root cause of these errors is the complexity and labor intensity of the effectivity system.

Figure 3.4 - Configuration Specification Errors are a Major Source of Rework¹⁴

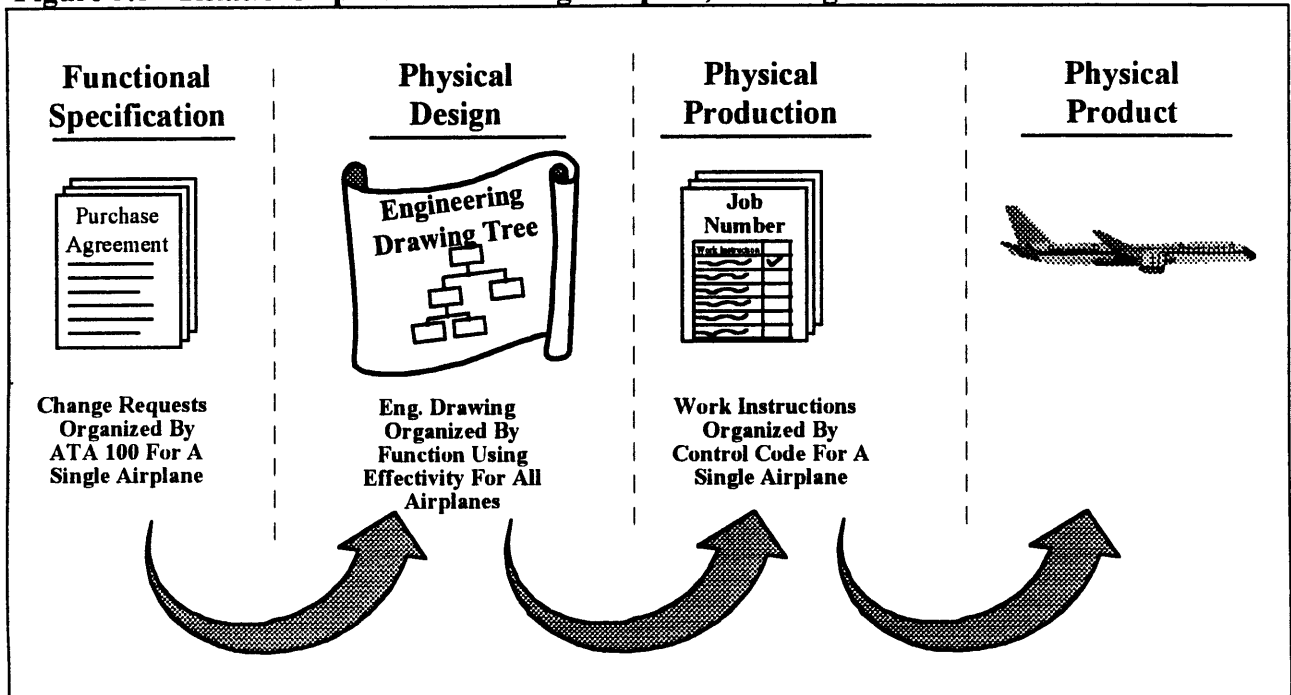


3.3 Disconnected Process Impairs Customer Configuration Decisions

Customer configuration decisions are documented in the Purchase Agreement using Change Requests which are organized by Air Transport Association Specification 100 standard. Since the engineering drawings are organized by the drawing tree using effectivity, the relationship between the Change Request and the Engineering Bill of Material is vague, undocumented, and fluid. Without an explicit relationship between the Change Request and the Engineering Parts List, option compatibility, cost analysis, and product performance are difficult to estimate. Figure 3.5 graphically displays the nature of these relationships.

¹⁴ Source Everett Engineering Quality Feedback Systems, Boeing Commercial Airplane Group, October - December, 1994.

Figure 3.5 - Relationship Between Change Request, Drawing and Work Instruction Unclear



Option Compatibility - The current process depends on the knowledge of key individuals in the organization to construct the proper relationships. This activity was described in the detailed process flow shown introduced in Section 2, Figure 2.1. The sub-process, "Identify All Impacted Engineering Definition", requires that key engineers read the Change Requests and identify all Engineering Drawings which must be tabulated with new Effectivities or re-designed altogether. Since identification of the impacted engineering is not apparent to the organizations who are developing the purchase agreement, option compatibility assessments are order of magnitude investigations only.

Cost - Cost of a customer unique feature can only be accurately assessed when the impact to engineering design, procurement and factory operations are understood. Impact to factory operations can only be assessed after the Engineering Bill of Materials has been modified to accommodate the customer unique feature. Again, the subtle relationship

between the Change Request and the Engineering Bill Of Materials undermines accurate cost analysis.

Product Performance - Aircraft performance is strongly influenced by the weight of the aircraft. Again, with out a crisp understanding of the relationship between the Change Request (functional configuration specification) and the engineering parts (physical configuration specification), the accuracy of the weight assessment is suspect thereby reducing the fidelity of the overall aircraft performance assessment.

3.4 Disconnected Process Limits Visibility to Past Designs

Effectivity obscures visibility into past design and encourages re-design. Effectivity does not provide a relationship between the optional feature and the engineering design. It simply relates a physical engineering design to all customers aircraft that have been configured with that particular design.. Because the relationship between the optional feature and the engineering design does not exist, engineers re-design unnecessarily.

Re-inventing design solutions for every new customer order is a major cost driver. Much of the cost of re-design is not visible to the engineering organization. As engineering creates new part numbers, planning creates new work instructions, Material orders additional inventory, and airlines provide additional spare parts support. All of these factors make unnecessary redesign an expensive proposition.

3.5 Disconnected Process Results In A Complex Manufacturing System

Without a relationship between functional specification, physical design and physical production, the manufacturing system is forced to manage all parts as variables. Today's manufacturing system does not know which parts are common to all aircraft versus which parts are related to optional features and consequently used on only selected aircraft. This

lack of information drives the manufacturing system to a single process that treats every airplane as a unique build. Today's system has been designed around a single process that allows for highest level of complexity, coordination and control. The result is a highly accurate but expensive system which fails to take full advantage of economies of scale in production.

Manufacturing System Forced To 100% MRP - Today the manufacturing system fabricates aircraft via subassemblies and zones. Manufacturing engineers are encouraged to level work loads in production areas by moving minor assembly operations out of control codes and into sub-assembly work centers. If the parts being assembled in these shops are related to optional features, the composition of the sub-assemblies becomes unique to a specific aircraft. When this happens, the manufacture of the assembly must be synchronized to the production schedule so that the correct aircraft gets the correct assembly.

Since the manufacturing system cannot discriminate between parts which are basic to all aircraft versus parts that are related to customer selected options, customer unique sub-assemblies proliferate throughout the supply chain requiring 100% MRP planning techniques to control production. This results in an increase of high risk inventory which can only be used on a specific customer's aircraft, and an overall increase in complexity to coordinate production of the entire supply chain.

Re-Sequencing The Production Line Creates Significant Re-work - With customer unique assemblies introduced early in the production sequence, any re-sequencing of the production line creates significant rework and re-planning. During normal business cycles, it is common for airline customers to delay or cancel orders. When an order is canceled or shifted, the production sequence and all customer unique assemblies must be either rescheduled (i.e. held in inventory) or modified to a new customer unique configuration.

Therefore, production line adjustments impose significant rework and confusion throughout the entire supply chain.

3.6 Aligning the Configuration Specification Throughout the Process Is A Point Of High Leverage

Looking back at the evaluation of the current process at Boeing, it is clear that the existing process is highly complex. However, causal loop analysis of the fundamental process reveals leverage points. A first order causal loop was created to understand the dynamics of the process. Figure 3.6 shows the loop placing emphasis on the design process. The causal loop of interest begins with the “Number of Customers”. As the number of customers increases, their desire for more optional features increases leading Boeing to offer a more complex and diverse set of options. As the number of optional features increases, the complexity of the relationships between the functional configuration specification and the physical design configuration specification increases thereby reducing the quality of the relationships. (Quality in this usage represents the number of people in the organization who can understand the relationship) As the quality of the relationships between the functional configuration and the physical design is reduced, the organization is able to identify fewer existing designs to meet existing functional configurations. As fewer existing designs can be identified to satisfy previously delivered functional configurations, unnecessary re-design is created. As unnecessary design is pursued, engineering productivity is reduced thereby increasing the cost of the aircraft and its selling price. As aircraft prices are increased, the number of customers is reduced.

This loop behaves as a balancing loop. The point of leverage in the process is in the ability to sustain high levels of quality on the relationships between the functional configuration and the physical design configuration. Today’s effectivity process is so naturally complex, that as new options are offered, the quality of the design relationships are destroyed resulting in errors, late deliveries and higher cost.

The same analogy holds true for the physical production process. The causal loop which emphasizes physical production is shown in Figure 3.7. This loop starts with an increase in customer orders. This increase in customer orders increases design activities which are focusing on effectivity tabulation. An increase in design activity, increases the number of designs which manufacturing must fabricate. As the number of possible designs increases, the quality of the relationship between physical design configuration and physical production configuration is reduced. As the quality of the relationship between physical design and physical production becomes more ambiguous, the number of customer unique assemblies increases. The more customer unique assemblies which are created, economies of scale in production decrease resulting in increased costs of production. As aircraft costs increase, aircraft prices increase resulting in a reduction in customer orders.

Again, the production loop behaves like a balancing loop. The point of leverage in the production process is the ability to handle a complex suite of design alternatives without interrupting the basic manufacturing processes that provide scale economies. The key to managing the complexity of design proliferation is to create and sustain accurate relationships between the physical design and the physical production. The lack of visibility between the production process, the part design and the optional feature adds complexity to the manufacturing system.

This thesis argues that the configuration process is the key to fundamentally simplifying the manufacturing system. By providing explicit relationships between the functional configuration, physical configuration and the production configuration, physical design may be stored in a design library and re-used to the maximum extent possible. By providing clear linkages from design in to the production process, the manufacturing activity may evolve around natural business streams which act to stabilize production, expand economies of scale and drastically simplify the entire manufacturing system.

Figure 3.6 - Causal Loop Analysis of Current Process Emphasizing The Design Loop

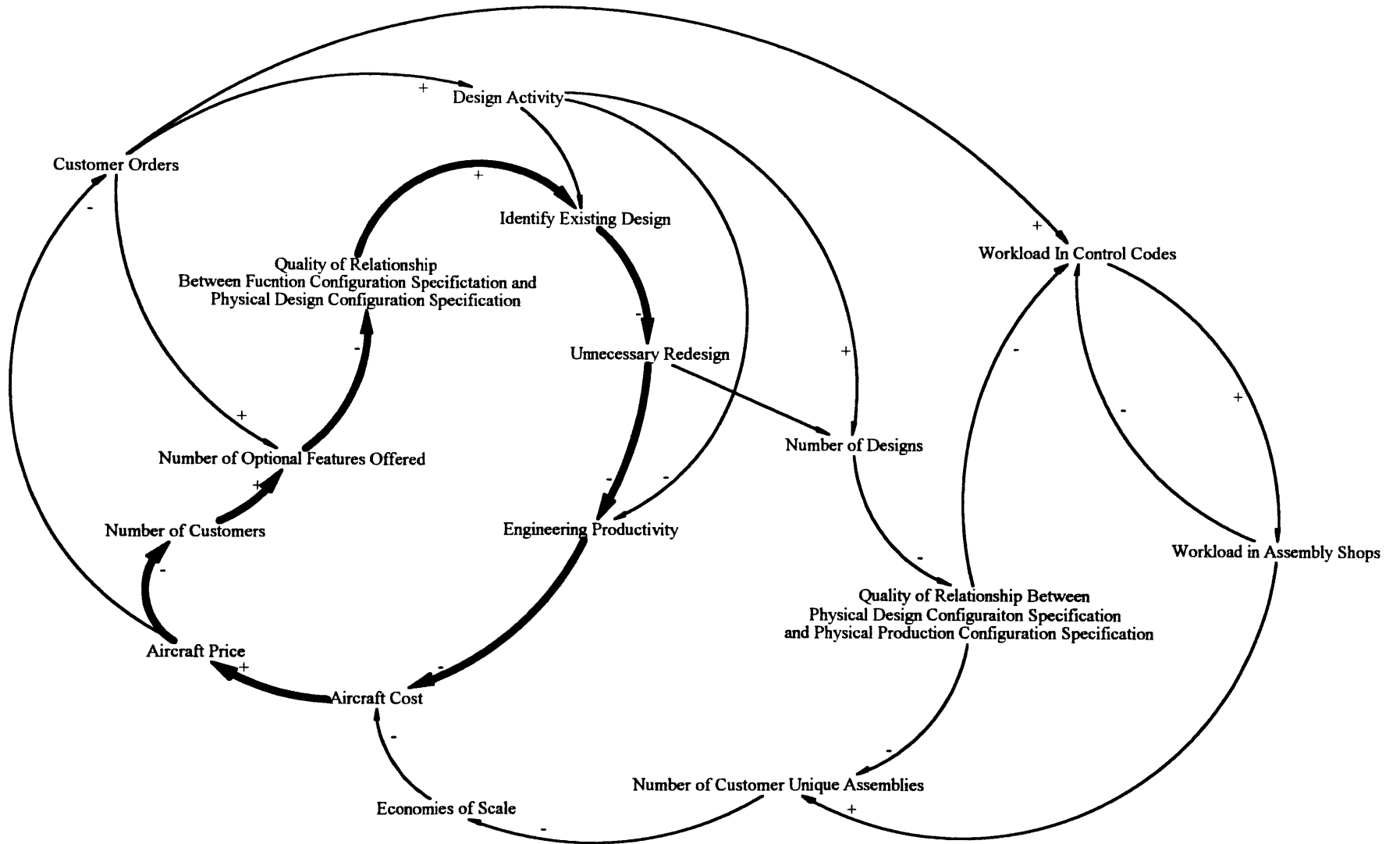
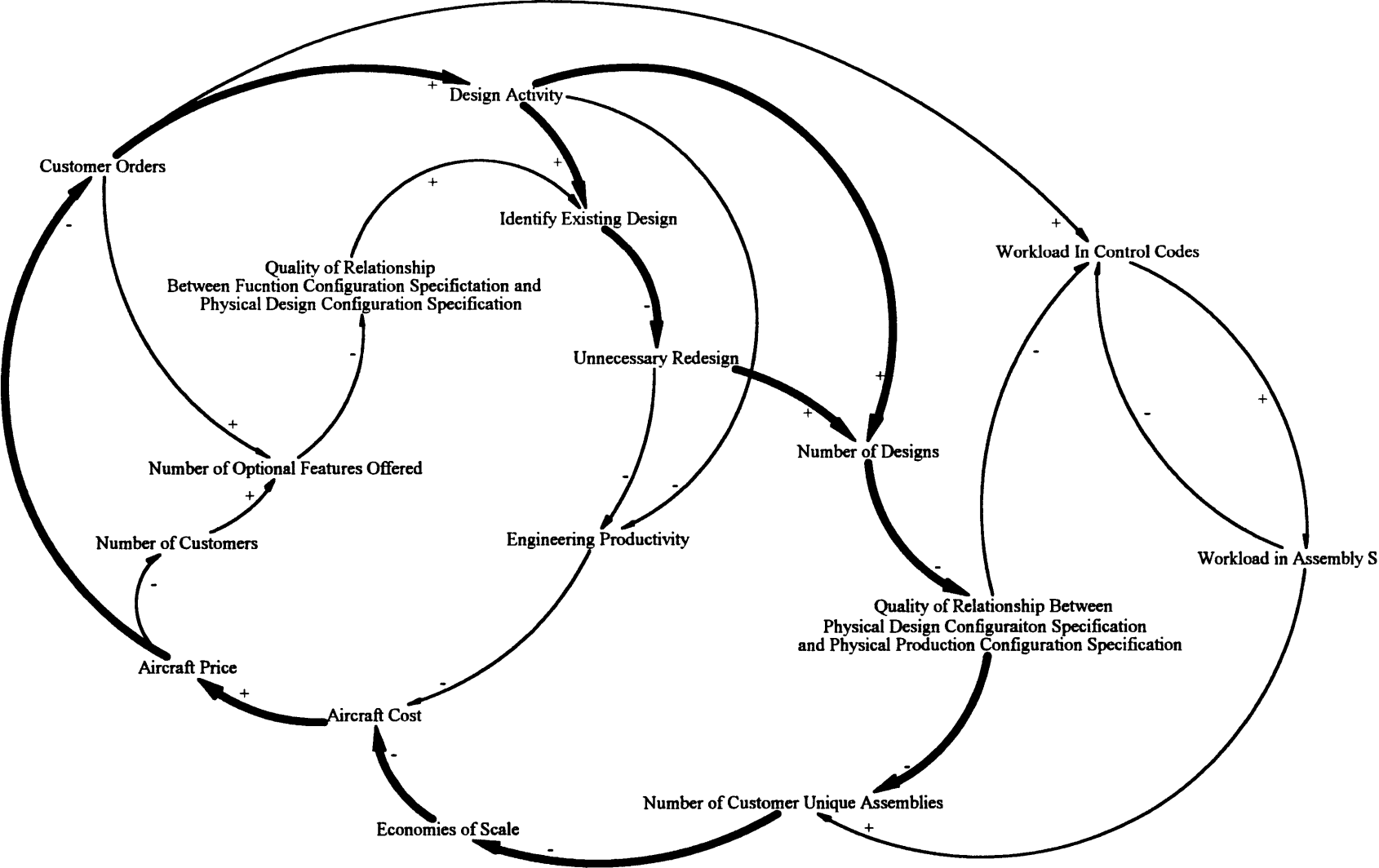


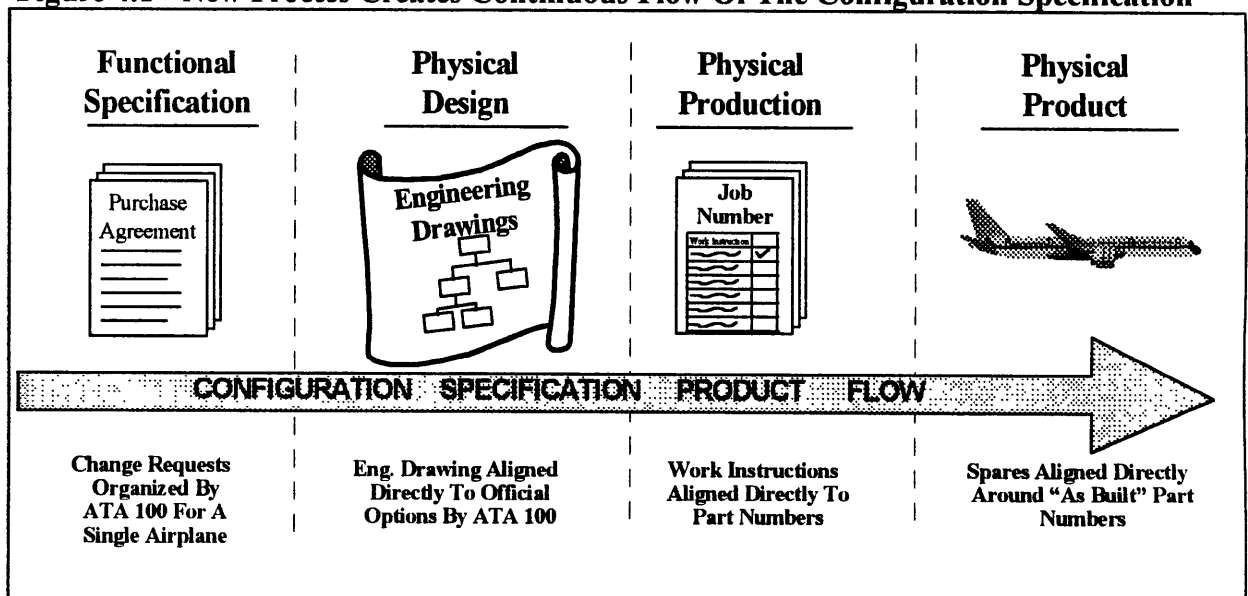
Figure 3.7 - Causal Loop Analysis of Current Process Emphasizing The Physical Production Loop



4.0 DESCRIPTION OF THE PREFERRED CONFIGURATION PROCESS

Creating linkages between each of the configuration specifications is the key to reducing the cost of Boeing aircraft. This section will provide a detailed description of a module based configuration specification process. A major objective of the new process is the alignment of the Functional Specification with Physical Design, Physical Production, and Physical Product as is shown in Figure 4.1. Alignment of these specifications is achieved by two fundamental changes: the creation of a data object called the module, and the elimination of effectivity from the physical design definition.

Figure 4.1 - New Process Creates Continuous Flow Of The Configuration Specification



As described earlier, Functional configuration specification is defined by the customer. The new process creates a product flow that explicitly maintains relationships between the Functional Specification, Physical Design, Physical Production, and Physical Product configuration specifications. These linkages eliminate the use of effectivity from the engineering drawing thereby eliminating the need for manual manipulation of the engineering drawing to control configuration. A significant portion of the cost savings inherent in the preferred process are attributable to reducing the labor intensity of the

configuration specification process. To accomplish this objective, a new data architecture and computerized configuration specification system must be developed.

4.1 Data Architecture Overview

The new configuration process begins with the customer expressing functional requirements as a set of certified options. The goal of the new data architecture is to explicitly define relationships between customer selected options, engineering design, work instructions, and physical product so that the physical design configuration specification, physical production configuration specification and Physical Product configuration specification can be derived.

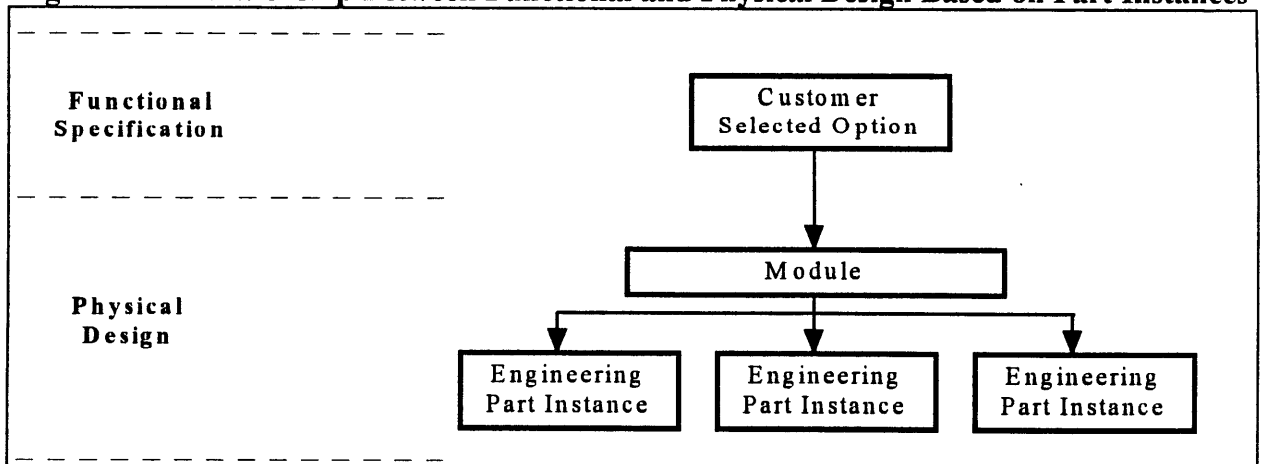
Relationship Between Functional Specification and Physical Design - The first step is to define the relationship between the functional specification (option) and the physical design specification (engineering drawing). The desired relationship must map single options into physical designs.¹⁵ In order to create this relationship, a methodology for accurately identifying the engineering design details must be established. Normally, a part number is uniquely and completely identified by the engineering design. However, on a commercial airplane, the same part number can be copied into a specific application in several places on a single airplane, and may satisfy different customer options. For example, a standard bracket for securing a wire bundle may be identified by a unique part number. However, one physical installation of the bracket may be needed to secure wiring for a temperature indicating system. A second physical installation of the same part number may be used to secure wiring for an optional light fixture in the bathroom. This leads to the problem of a single part number being used multiple times to satisfy multiple options. Therefore, specification of a part number is inadequate to support the proposed

¹⁵ A single option often requires several engineering designs from several functional areas to fully implement the full functionality of the option. Functional design areas include structural design, electrical design, mechanical systems design, avionics design. In addition, a single option often requires several design changes to fully provide customer's intended functionality.

configuration process. To solve this problem, part numbers are associated with part location data. The location data is specified in terms of the aircraft coordinate system. The aircraft coordinate system is a unique coordinate system unique to each major aircraft model. Location is specified by three parameters (1) Station line, (2) Buttock line, and (3) Water line. By specifying part number with location information, each installation of the part can be uniquely identified. The name for a part which has been associated with its installed location in the aircraft coordinate system is defined as a *part instance*¹⁶.

Options can now be related to physical engineering design using the part instance methodology described above. The logical entity that groups part instances into an option is defined as a **module**. The module relates several part instances to a single option as is shown in the data architecture shown in Figure 4.2. Therefore, an option can be described as the functional intent of a customer selected feature. A module represents the physical manifestation of that option expressed as a collection of engineering part instances.

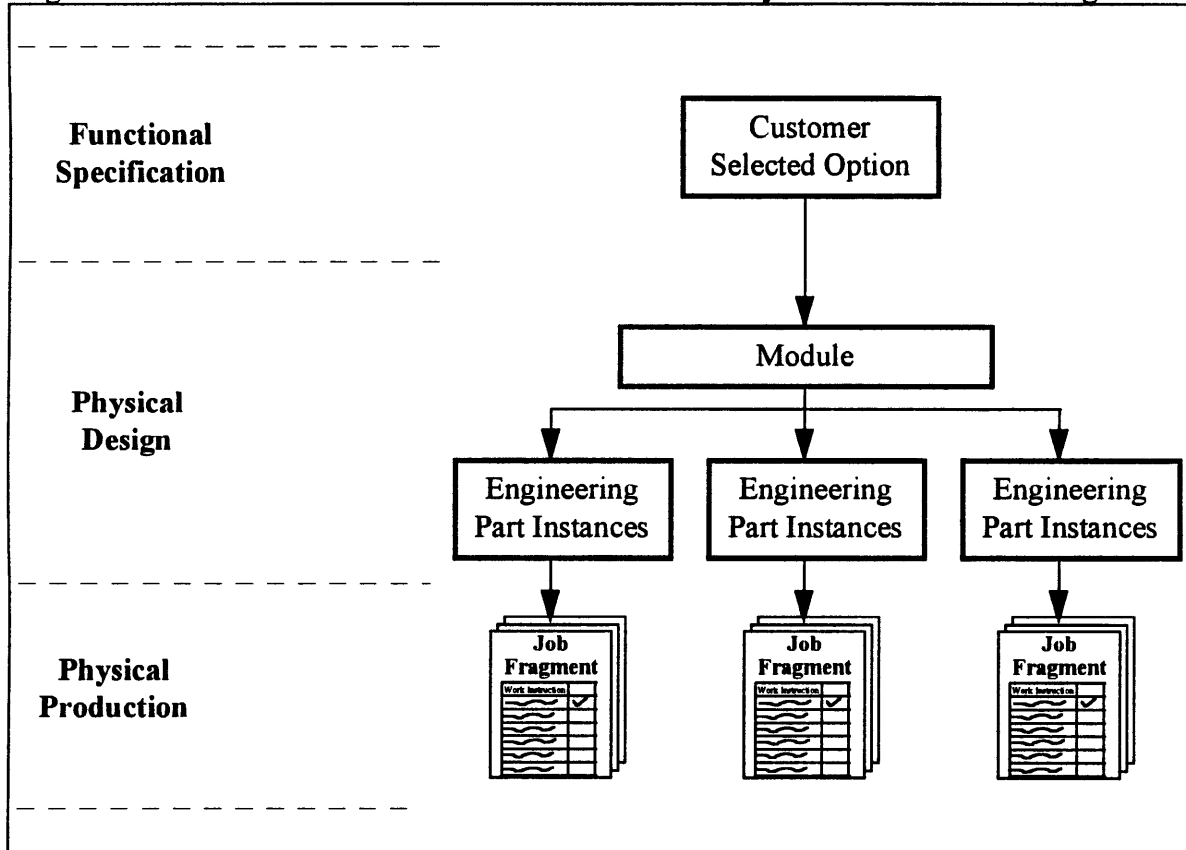
Figure 4.2 - Relationship Between Functional and Physical Design Based on Part Instances



¹⁶ Concept first developed by Carol Pittman at Boeing Commercial Aircraft.

Relationship Between Physical Design and Physical Production - Physical production does not directly relate to the Function specification but to the physical design through the part instance. Physical production represents the work instructions (job fragments), tools and test procedures required to install and certify a part instance. Therefore, the essential relationship is between the part instance and the job fragment¹⁷. The data architecture presented in Figure 4.2 has been extended to include the relationships between physical design and physical production. This extension of the data architecture is shown in Figure 4.3.

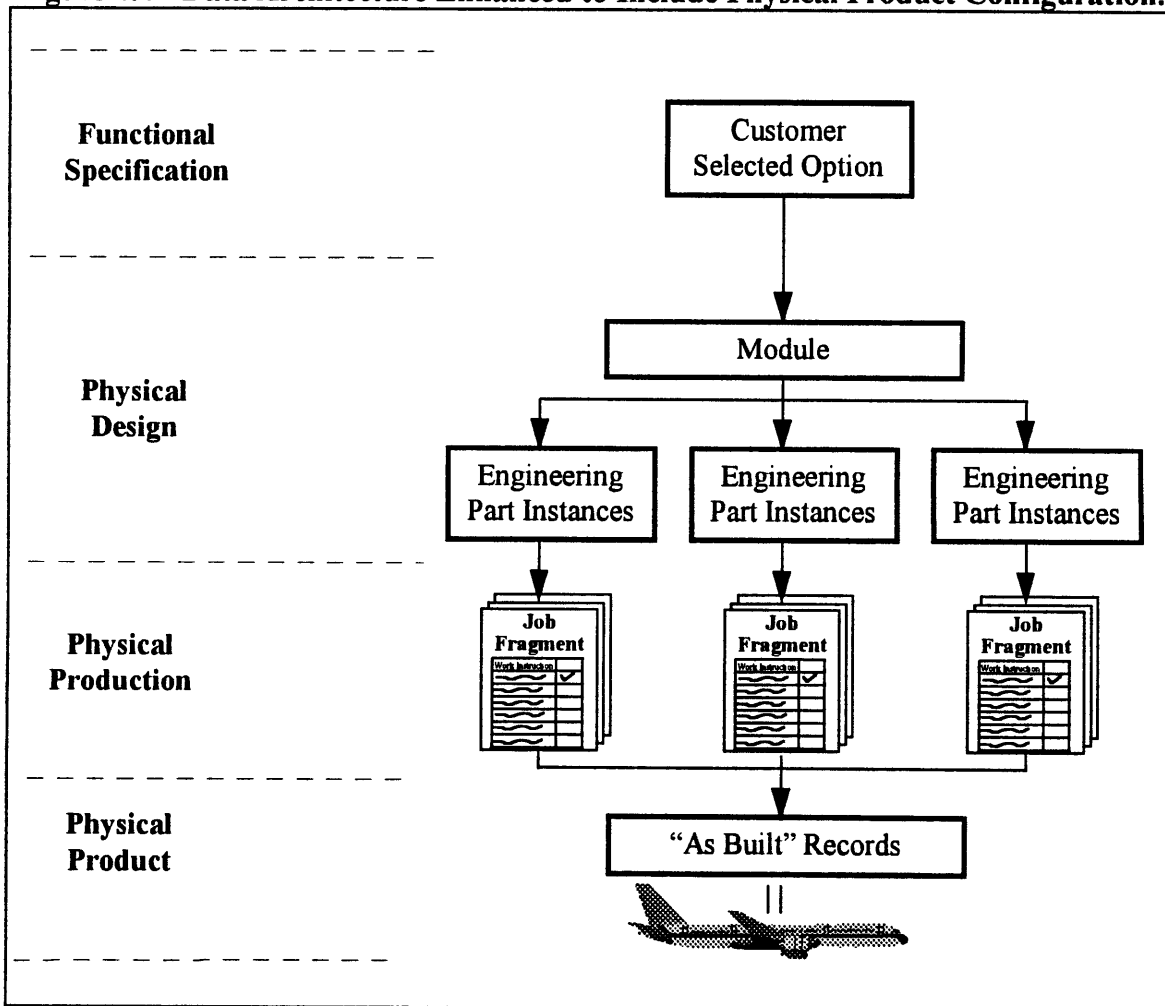
Figure 4.3 - Data Architecture Enhanced to Include Physical Production Configuration.



¹⁷ A “Job Fragment” is a set of factory work instructions necessary to install the engineering part instance of interest. After all parts have been identified, job fragments are integrated together to form a complete set of factory work plans and instructions.

Relationship Between Physical Production and Physical Product - Physical production represents the work instructions, tools and test procedures to create the product. The relationship between physical production and the physical product is the record that documents the configuration which was actually delivered to the customer. The actual configuration may differ from the planned configuration because of factory rework, or last minute design changes. The relationship between the planned configuration and the actual delivered configuration is the “As Built” record. The “As-Built” record is directly related to the work instruction. The data architecture has again been extended to include the relationship between physical production and physical product and is shown in Figure 4.4

Figure 4.4 - Data Architecture Enhanced to Include Physical Product Configuration.



4.2 Configuration Process

The data architecture described in the last section defines a fundamentally different configuration process. This process begins with customer specification of a set of options which becomes the basis for deriving all other necessary configuration specifications. The Functional Configuration specification is defined for a single customer airplane. This specification is called the Customer Specific Option Specification (CSOS)¹⁸. The CSOS contains the keys to all relevant information about the aircraft. Information includes:

(1) Manufacturing Serial Number - Five digit numeric code assigned to an aircraft at the beginning of production. This identifier stays with the airplane from its first conception to retirement.

(2) Customer Identifier - Three character abbreviation of the Customer. (e.g. United Airlines is represented by "UAL")

(3) Aircraft Type Code - Code that reflects the major and minor model for the aircraft. In the code 44F, the first digit represents the major model (4=747) and the second two digits represent the minor model (4F=-400 Freighter)

(4) Status Code - Information describing the maturity of the aircraft order. This code describes whether the aircraft is in a proposal state or has been accepted as a firm order by the customer.

(3) Delivery Date - Numeric field describing delivery date of the aircraft to the customer.

(4) Line Number - Four digit number specifying the position of the aircraft in the production line.

(5) Option Identifier - Ten digit alpha numeric code that specifies the option. (e.g. the option identifier for a carbon brakes temperature indicating system is **3246CG5002**)

Thus, options which are specified in the CSOS are of four basic types. These include the Major Model Option (e.g. 747, 737, 777), the Minor Model Option (passenger, cargo, freighter), options which have been previously engineered/certified and newly defined options which have not. The Airplane Specific Configuration Table contains unique

¹⁸ Concept first developed in DCAC program at Boeing Commercial Airplane Company

identifiers for all four types of customer selected options and provides a complete Functional Configuration Specification for the aircraft. An example of a typical Customer Specific Option Specification Table is shown in Figure 4.5.

Figure 4.5 - Typical Customer Specific Option Specification Table

Mfg. Serial Number	Customer Identifier	Aircraft Type Code	Status Code	Option Selection						
				Major Model	Minor Model	Engineered & Certified Options			New Options	
25768	UAL	44F	- Proposal - Accepted	747	400F	5610PD4001	2162PD4002	●●●	5112PD1001	●●

After the functional specification has been defined, the relationships contained in the data architecture (see Figure 4.5) are used to derive the configuration specification of the physical design, physical production, and physical product. The options have an explicit relationship to the module, the module identifies the engineering part instances, the part instances relate to the job fragment containing work instructions, tools and test procedures, the job fragments relate to the “As Built” records.

4.3 Problem of Inter-Dependency

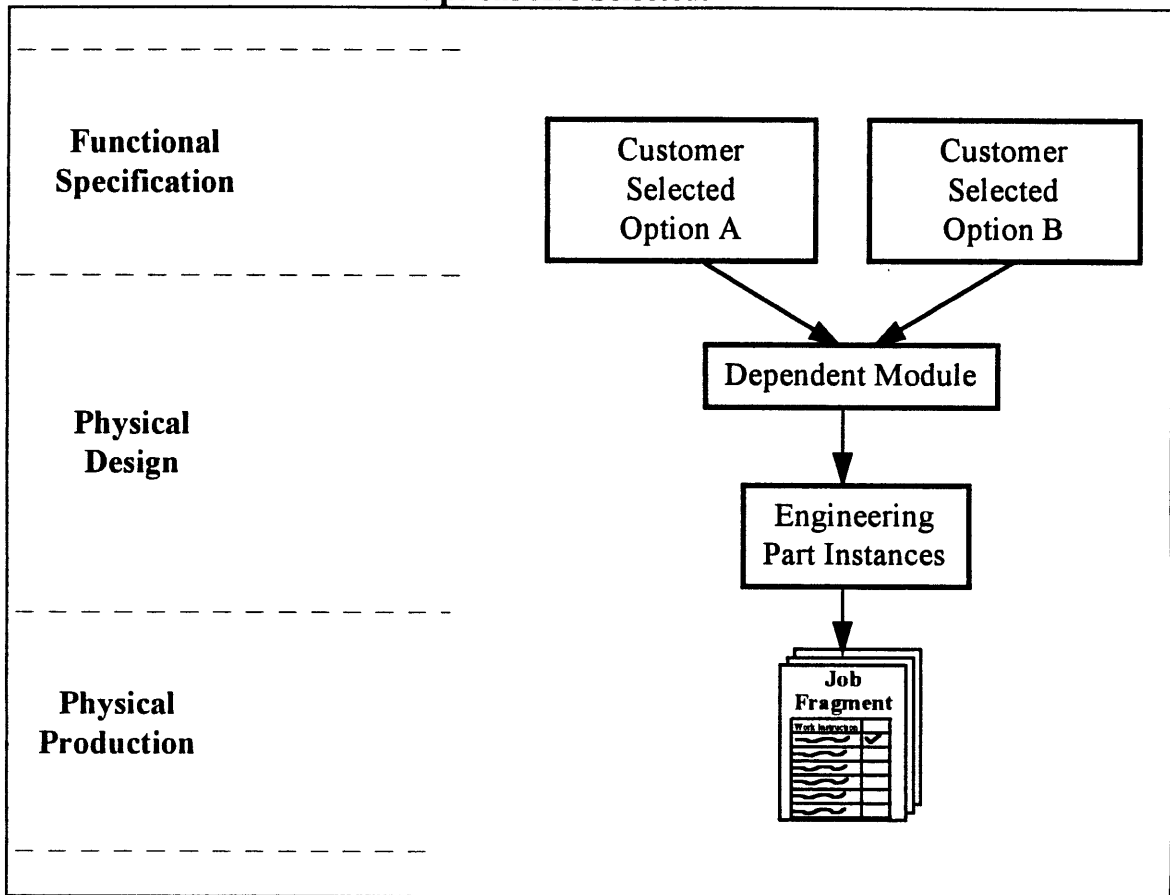
There exist situations where the selection of an option is contingent upon other options having been previously selected. For example, in order to select the “Steel Brakes Temperature Indicating System” option, the customer must have previously selected the “Segmented Steel Rotors and Brakes” option. This example describes inter-dependencies between options. Inter-dependencies may occur at two levels in the configuration specification: the functional level and the physical design level. At the functional level, dependencies between options are based on functionality. These dependencies are well understood, and relatively infrequent. For example, the 757-200 aircraft offers 273 standard options¹⁹. Only a few dozen of these options have an inter-dependencies. The relatively limited nature of these inter-dependencies at the functional level can be managed using a simple computerized rules engine imbedded inside the functional configuration specification process.

The second level of dependency is at the physical design level. At this level, part instances which configure the airplane are dependent on a combination of options having been selected. For example, the aircraft might get support bracket “A” if a HF radio option is selected, or support bracket “B” if the VHF radio is selected or support bracket “C” if the HF and VHF radio’s are selected at the same time. In this case, the module containing support bracket part instance is not configured when a single option is selected. It is only configured when a particular combination of options is selected.

In order to deal with inter-dependencies at the part level, a **dependent module** is created specifically to configure part instances which are dependent on the selection of a combination of options. This is shown graphically in Figure 4.6.

¹⁹ Renton Division Customer Engineering, Configuration Specification Model 757-200 Revision G, Document Number. D924N104, The Boeing Company, December 15, 1993

Figure 4.6 - Dependent Modules Configure Part Instances Only When A Combination Of Options Are Selected.

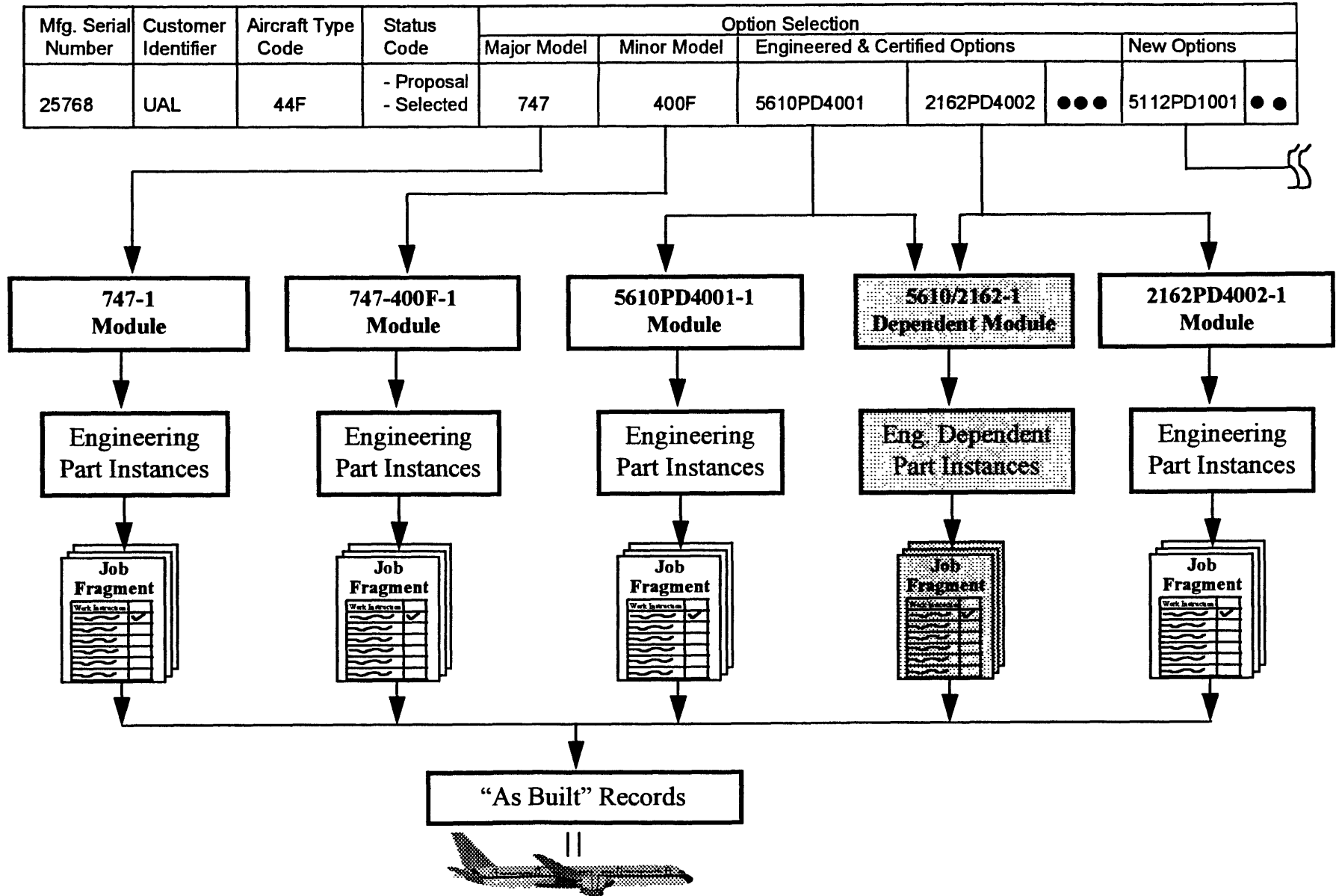


In summary, the configuration process begins with the creation of the functional configuration specification as defined by the Customer Specific Option Selection (CSOS) table. Information in the CSOS table in combination with the data architecture and configuration software are used to first configure the physical design by selecting the primary (non-dependent) modules. After the primary modules have been selected, dependent modules are then selected based on the combination of options defined in the CSOS table. After all modules have been selected, part instances, work instructions and tools are immediately activated in the physical production configuration specification. As the aircraft is being produced, “as planned” build records are updated to reflect the “as built” configuration. The complete configuration process is shown graphically in Figure

4.7. It should be noted that computerized rules engines are required to select legal combinations of options, primary modules and dependent modules. Once all modules have been selected, the data architecture automatically configures the engineering part instances and work instructions.

The module is the cornerstone of the preferred configuration process. It contains the necessary information to create the Engineering Bill of Materials as well as the work instructions. It must be stressed that the module must not be confused with “interchangeable modular assemblies” which are weight prohibitive. The fundamental purpose of a module is to align the functionality with the physical design.

Figure 4.7 - Summary of Configuration Process and Data Architecture



4.4 Evolution Of Business Streams

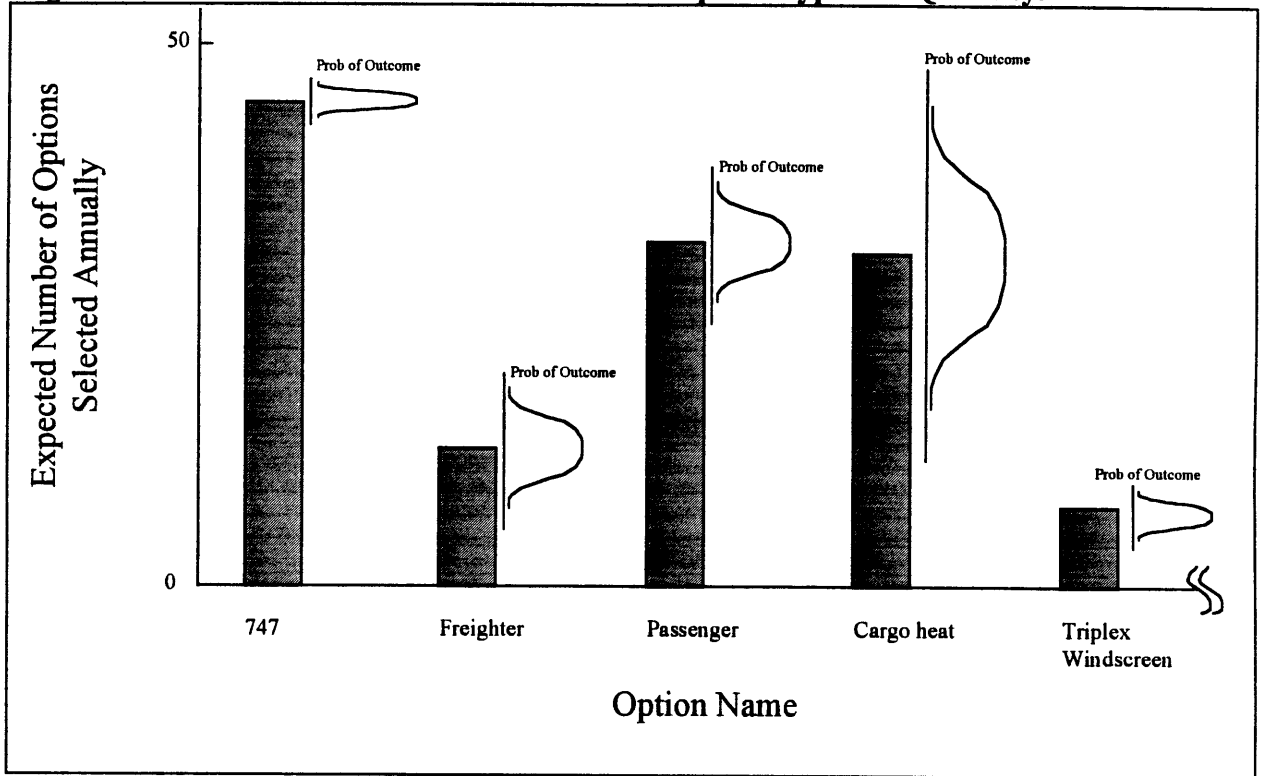
Modules align the functional configuration specification with the physical design and production specifications. One of the powerful aspects of this module based configuration specification process is the potential impact it can have on factory operations. Today the factory builds each aircraft in more or less job shop environment. Every part is treated as unique and is manufactured to order per a labor intensive MRP process. Modules allow the factory to recognize which parts in the physical design belong to a particular option or combinations of options. For example, the 747 major model module identifies all parts in the physical design which are common to every 747 which rolls off of the production line. With this information, manufacturing personnel can now re-design the production sequence to build the relatively long lead hardware (common to the basic model) prior to the completion of the Customer Specific Option Selection table. These basic major assemblies can then be used in later stages of production thereby significantly reducing the cycle time. (Cycle time is the time measured from definition of the purchase agreement to delivery of the aircraft.)

Separating the production into business streams²⁰ has been a major initiative for Boeing Commercial Aircraft Group. Modules are a key enabler of the business stream concept. As engineering part instances are aligned with the option, forecasting for part requirements can be accomplished by assessing the probability that an option will be selected. Figure 4.8 shows a possible forecast by option type.

The forecast shown in Figure 4.7 shows two very important pieces of information. First it shows the expected value of the forecast with respect to each option. Second it also shows the probability bands which reflect the certainty of the estimate. For example, the expected number of 747 major model options which are expected this year is 44 with a error band on this estimate of only 3 units. This estimate can be contrasted by the forecast

²⁰ Concept of Tailored Business Streams first developed in BCAG, 1992.

Figure 4.8 - Possible Aircraft Forecast Based on Option Type and Quantity.



for the Cargo Heat option. The expected number of 747 aircraft delivered with the cargo heat option is 40 with an error band ranging from 47 (all 747's will get cargo heat) to 25 units. Since modules relate the option to the parts, forecast information can be applied to individual part instances.

This type of part instance based forecasting can be used to radically simplify the planning and ordering process. The manufacturing stream responsible for producing the high volume and stable part of the product flow (e.g., 747 basic part instances) can be implemented with minimal planning as compared to the manufacturing stream which is producing highly variable parts (e.g., cargo heater related part instances) used on only a few aircraft. The high volume and stable business stream manufactures stable product forms, at fixed rates which are independent of the optional features selected by the customer. This part of the manufacturing system does not require full MRP planning and

ordering. Rate based, pull system can be used with Kanban or card control to fulfill ordering requirements. These well known production methods simplify the manufacturing system and also reduce inventory levels.

On the other hand, options that are used on only specific aircraft, would be managed by a business stream which used full MRP planning. Since these parts are not common to every line number, they must be specifically scheduled control code.

The relationship created by the module between the option to the part instance has the potential to re-organize the factory. Since manufacturing engineering now knows which parts support different customer options, they can attempt to design the manufacturing sequence to keep these highly variable parts toward the last possible stage in the build sequence. This will usually move the variability in sub-assembly configurations out of the back shop and into the major control codes. This will reduce the number of assembly part numbers produced by subassembly shops resulting in reduced complexity and increased learning curves. The bottom line: Configuration variation, which today is spread throughout the supply chain, will be concentrated toward the last appropriate stages of production, which should result in manufacturing system simplification and reduced costs.

5.0 MODULE BASED CONFIGURATION SPECIFICATION APPLIED TO AIRCRAFT FUSELAGE BULKHEAD

This section applies the data architecture and configuration specification methodology developed in section 4 to a typical aircraft bulkhead structure. The structure, pictured in Figures 5.1 and 5.2, is the “Body landing Gear Support Bulkhead” located on the 747 aircraft at station 1480. It is part of the section 44 major assembly which includes the upper fuselage monocoque, floor grid, wing box center section, landing gear beams and system installations. This section will describe the entire 4 phase process beginning with the development of the functional configuration specification through the specification of the configuration rules which derive the physical design and production configuration specifications. This example verified the feasibility of the module based configuration specification.

5.1 Phase One: Identification of the Functional Configuration

The total functionality provided by the Body Landing Gear Support (BLGS) bulkhead is complex and interdependent. These include, but are not limited to, load transmission, landing gear support, corrosion resistance, pressure containment, wire bundle support, and systems support. The objective of phase one, is not to describe the total functionality of the product, but to reveal the functional configuration from the menu of choices that are presented to the customer. As described in section 4, the customer selected functionality is documented in the Configuration Specification and consists of approximately 300 customer selected features. These include things like the basic model (i.e. 747 passenger), triplex windscreen, heating the lower lobe of the cargo bay, incorporation of class divider in the passenger compartment.

Figure 5.1 - 747 Fuselage Structure Showing Body Landing Gear Support Bulkhead

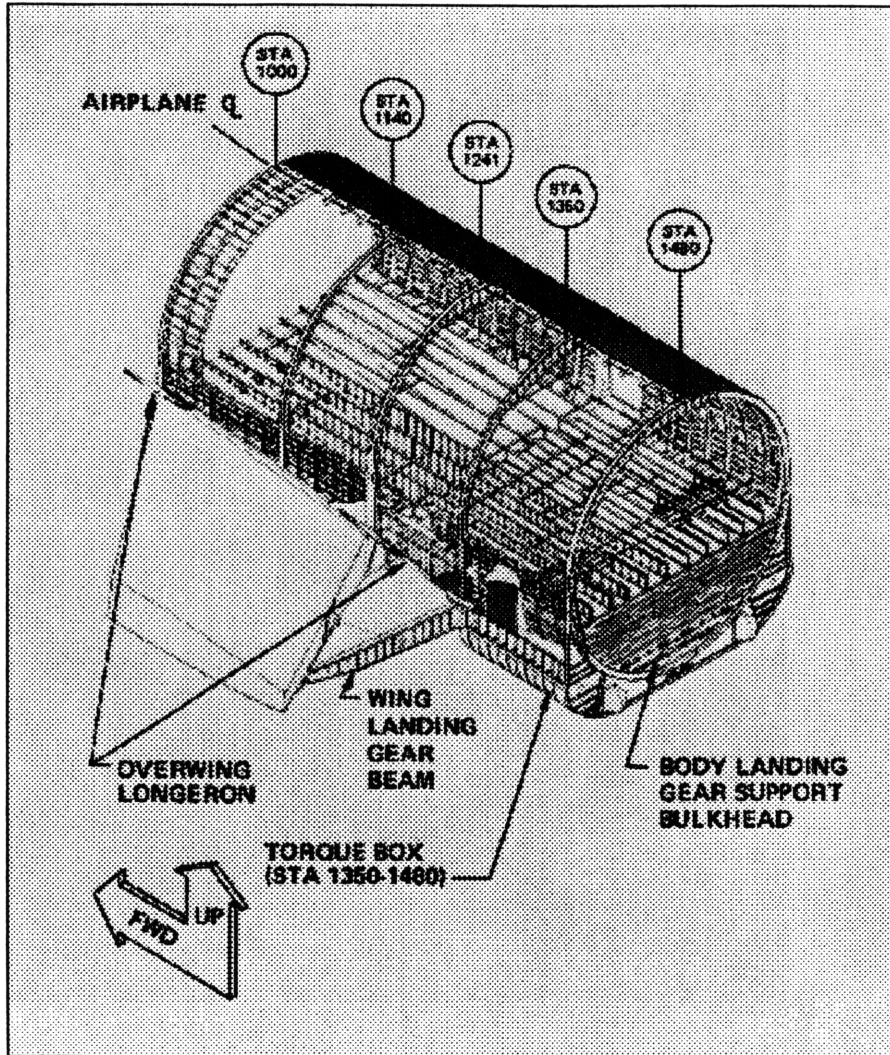
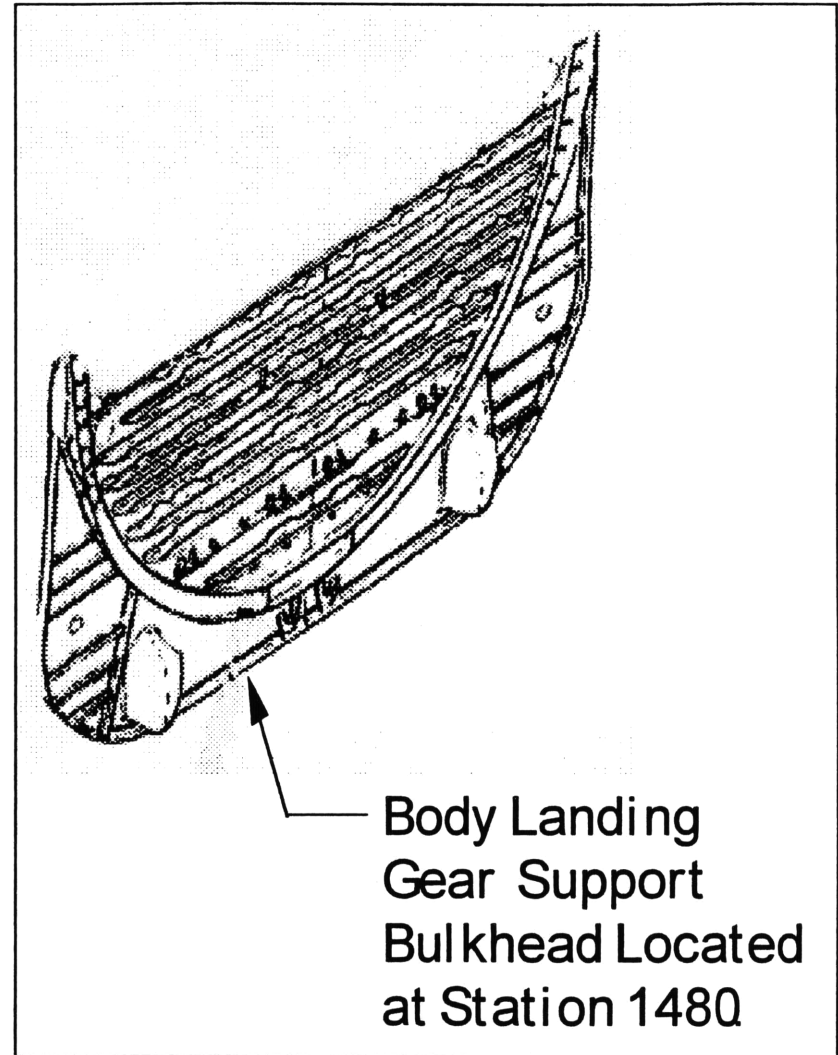


Figure 5.2 - Body Landing Gear Support Bulkhead



The functional configuration as it applies to the BLGS bulkhead was established by reviewing the Configuration Specification and conducting interviews with subject matter experts to understand the impact of the functional specification on the physical design. The relevant Functional Configuration Specifications as they apply to the bulkhead are shown in Table 5.1.

Table 5.1 - Configuration of BLGS Bulkhead Dependent on Selection of 6 Options.

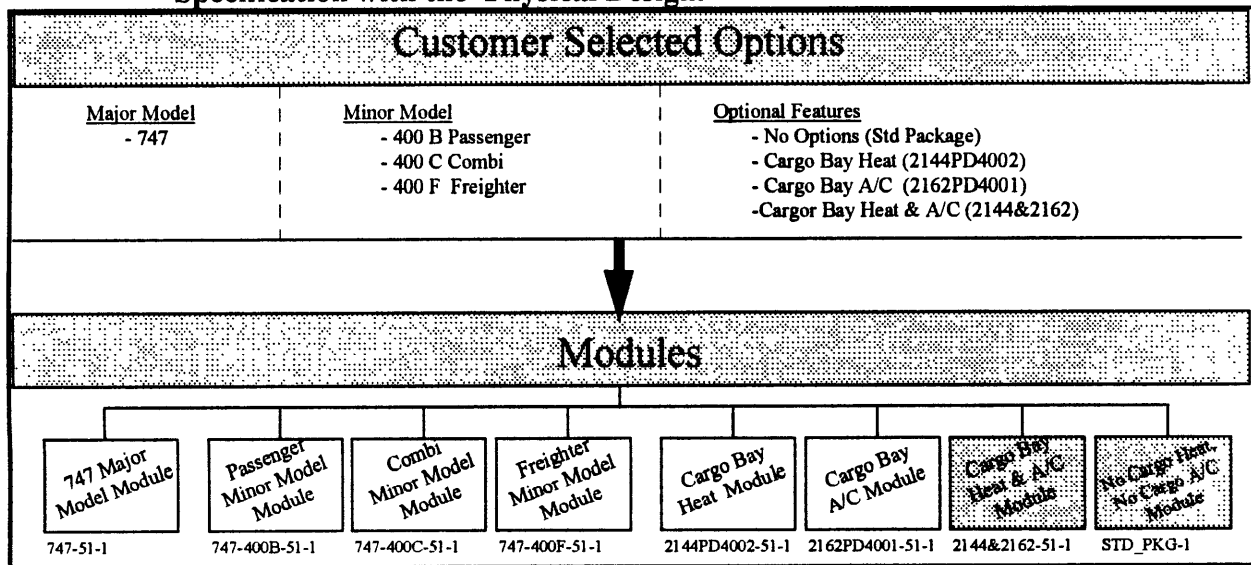
Option Type	Available Selections
Major Model Option	747 Aircraft
Minor Model Options	Passenger Aircraft Cargo Aircraft Combi Aircraft
Optional Features	Lower lobe cargo bay heater option Lower lobe cargo bay air-conditioning option

These six customer selected options plus the basic bulkhead design completely describe the Functional Configuration as it relates to the physical design specification of the BLGS bulkhead. It should be noted that the combinations of options are physically inter-dependent. For example, a customer is allowed to select either the passenger, freighter, or combi option but cannot choose these options in combination. Also, the customer may select lower lobe cargo bay heating or air conditioning or both. The creation of the rules base to adequately constrain the selection of option combinations are discussed in section 7.2.

5.2 Phase Two: Definition of the Module Architecture

As described in Section 4, the module relates and aligns the Functional Configuration Specification with the Physical Design Specification. Therefore modules must not only relate single options to the physical design but also physical combinations of options that together define the physical design. The relevant options for the BLGS bulkhead are the 747 major model option, the passenger, combi, or freighter minor model options, and the cargo bay heat and cargo bay air conditioning option. Modules were created for each of these functional specifications. Since selection of the cargo bay heat and cargo bay air conditioning options in combination altered the physical design, dependent modules were created. The resulting module architecture for the BLGS bulkhead is shown in Figure 5.3.

Figure 5.3 - Modules Created for BLGS Bulkhead Align the Functional Configuration Specification with the Physical Design.



Note the numbering scheme for each of the modules as shown at the bottom of Figure 5.3.

Module identification is defined by three major parts. The first part identifies the parent option as defined in the Configuration Specification. The second part defines the Air Transport Association (ATA) chapter describing the type of engineer part instances contained inside the module. (In the bulkhead example, -51 represents the ATA chapter for aircraft structures.) Finally, the third part of the module identifier represent revision

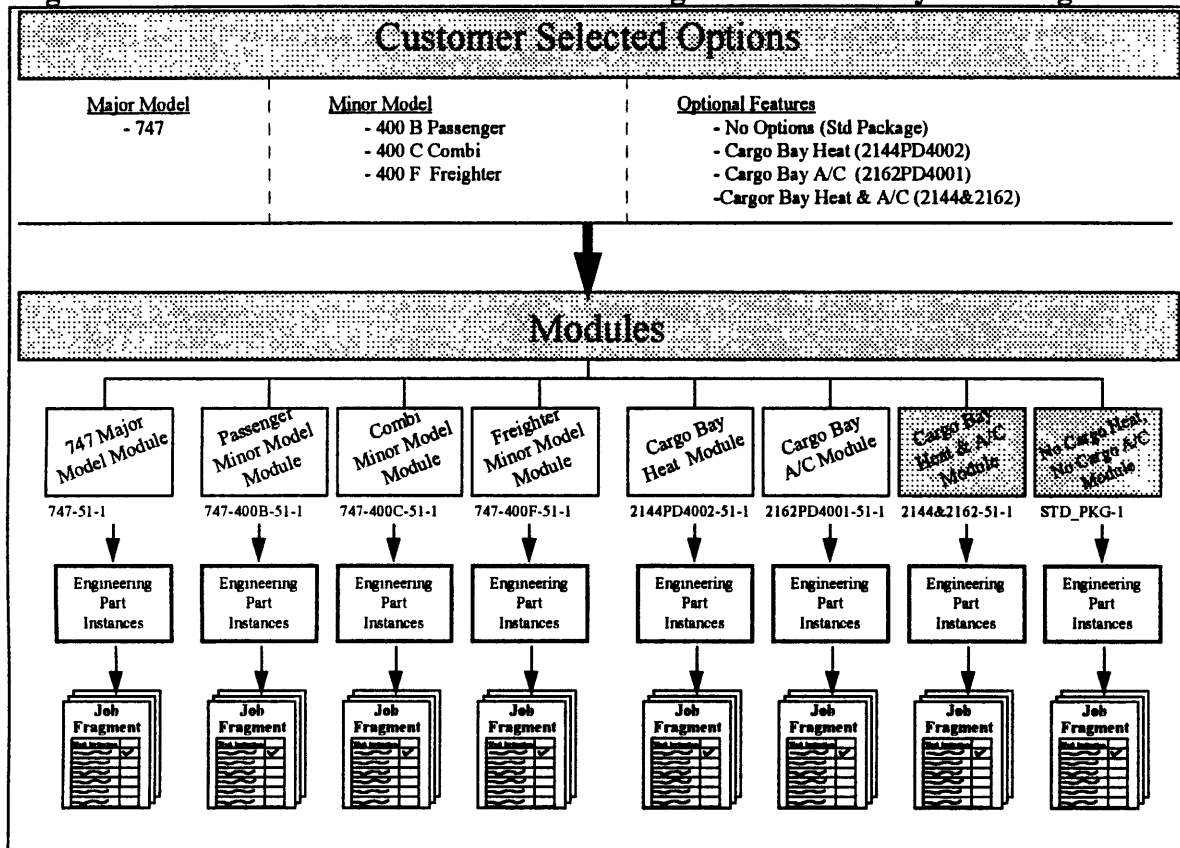
level. Modules, unlike options, represent the **physical** manifestation of the intended functionality. Revision levels for modules follow “pure part number control” to clearly establish uniqueness. Pure part number control requires that a parts/modules be re-identified whenever form, fit, or function are altered up to the point of part interchangeability.

5.3 Phase Three: Incorporation of Engineering/Manufacturing Data into the Module

The goal of phase three is to define the physical design and production configuration specifications around the functional configuration specification using the module architecture. The key to the module based product architecture is to align all three configuration specifications. For the BLGS bulkhead, this alignment is represented schematically in Figure 5.4. To accomplish this, existing engineering data had to be converted from the effectivity based configuration specification and cross tabulated against the functional configuration specification.

Discussions With Design Lead Important Part of The Process - Initial efforts to determine design definition were thwarted due to the complexity of the effectivity tabulation. The existing bulkhead design is described by 577 pages of effectivity tabulation blocks at the final assembly and collector drawing level. (similar to example described in Figure 3.3). In addition, installation drawings contained approximately 346 pages of effectivity tabulation. Although working through all the effectivity codes is a feasible method for determining design configuration, the size and complexity of the tabulation precluded this method from being pursued. Discussions with design leads were the key to unlocking the physical design. The design lead was able to identify all active configurations directly from memory. It was clear that the designers knew the configuration they wanted to specify but were unable to clearly communicate design intent using current effectivity based methods.

Figure 5.4 - Data Architecture For Bulkhead Align Function to Physical Design

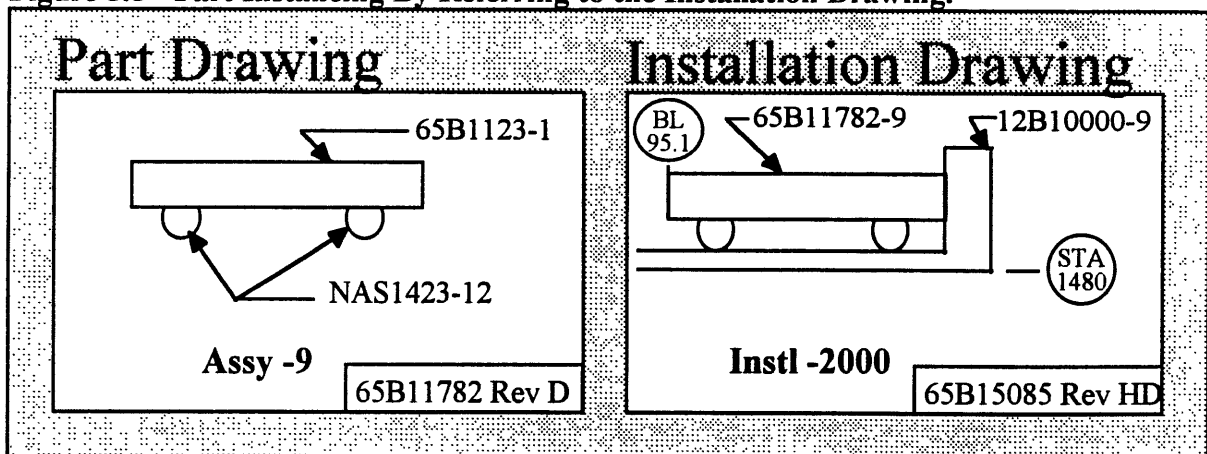


After active engineering tabulation blocks were identified, a cross tabulation analysis was completed to determine those engineering part instances which supported the basic 747 major model module, the passenger/combi/freighter minor model modules, or the cargo bay heating/ air conditioning modules. Cross tabulation was accomplished by using PLINQ (Boeing internal parts retrieval software) to download part data into Microsoft's Access data base program. The cross tabulation was conducted in Microsoft Access. Cross tabulated part data was then grouped into the appropriate module by noting the combination of final assembly configurations a particular part supported. For example, if a part was found on the final assembly drawings which describe the passenger, combi and freighter configurations, then that part is used on all 747's and is therefore grouped into the 747 major model module

Problem of Part Instance - Cross tabulation analysis revealed that several parts were used in different quantities in different configurations of the aircraft. This meant that the same part was being used in different locations to satisfy different functional specifications. This issue made the methodology described in section 4 particularly important in order to classify each part in the correct module specifically and accurately.

The part instance is defined by associating the part number with the part's physical location in the aircraft coordinate system. This information can be directly applied as a characteristic or property of the part number or it may be derived by referring the part to the installation drawing which locates the part in the aircraft coordinate system. The latter method allows a part to be identified without manually coding the part location into the module. An example of the latter approach is shown graphically in Figure 5.5. Figure 5.5 shows the physical design of a support flange which contains the 65B11782-9 assembly. To create the part instance of the 65B11782-9 assembly, the part number must refer to the 65B15085-2000 installations drawing. The 65B15085-2000 installation drawing picture sheet locates the part in the aircraft coordinate system by denoting station and buttock line position identifiers explicitly on the picture sheet.

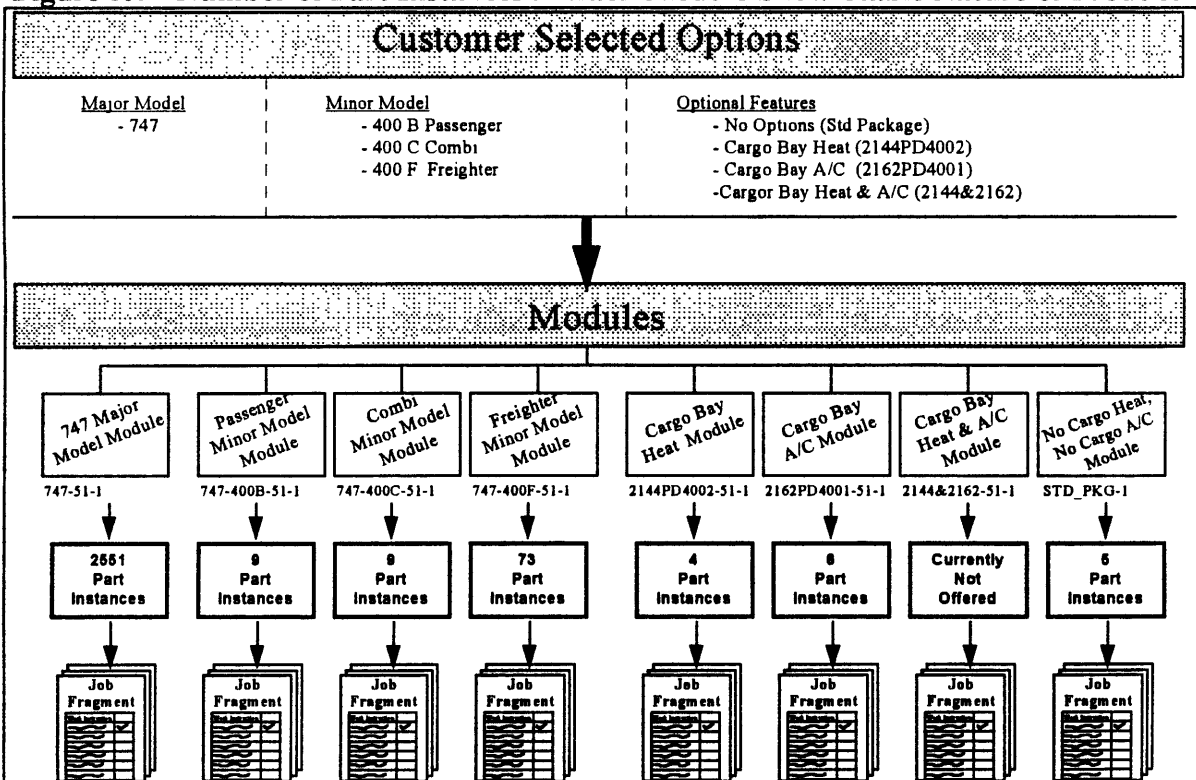
Figure 5.5 - Part Instancing By Referring to the Installation Drawing.



The location information on the installation drawing uniquely identifies the part thereby creating the part instance for the 65B11782-9 assembly. (It should be noted that, as a rule, the installation drawing, or a drawing similar to it, describes parts in the aircraft coordinate system and can always be used to define the part instance.) By using the part instance methodology described above, all parts in the BLGS bulkhead were uniquely identified and grouped into the correct module.

Packaging Bulkhead Engineering Data into Applicable Modules - After having defined all part instances, cross tabulation results were used to incorporate the engineering data in the modules. A summary of the parts instances in each module is presented in Figure 5.6. These numbers show that over 97% of the part instances are common to the 747 major model. This means that every 747 aircraft that travels down the assembly line will always require the parts contained in the 747 major model module. Since these parts are on every build sequence, full MRP planning of these major model part instances is not required. Parts ordering and management may be simplified using rate scheduling tools in place of full MRP.

Figure 5.6 - Number of Part Instances in Each Module Show Stable Nature of Product



Modules Contain A Wealth of Attribute Data At The Part Instance Level- Figure 5.6 shows the number of part instances in the various modules. Figure 5.7 details the actual content in a module. The module has been structured to contain a variety of important engineering data beyond the simple definition of the part or part instance. These data include process specifications, certification status, part availability line number, color/finish specifications, Material Identifier (MI) code numbers, Raw material types, and a host of other part characteristics. Figure 5.7 shows the Airplane Specific Configuration Table for the BLGS bulkhead describing, in detail, the definition of the 2144PD4002-2 (cargo bay heat) module. The definition of the module includes all of the part instance data required to configure the BLGS bulkhead for cargo bay heating as well as other important engineering data described previously.

Figure 5.7 - Detail Definition Of 2144PD4002 Module Reveals Part Attribute Data

AIRPLANE SPECIFIC CONFIGURATION TABLE												
A/P ID.			Delivery Date			Line #			Module		Module	
26852- UAL-44F			6/94			1044			747-51-1		400F-51-12	
									Avail. LN1039		Avail. LN1025	
											2144PD4002-31-2	
											Avail. LN1015	

P/N	Qty	Refer To Instl	STA	WL	BL	Part Availability	Approval Status	Finish Code	Color Code	MI Code	...
65B10005-22	1	65B15085-1061 RevHD	1440	56	-89	LN1039	Production	F18.6	.	.	
65B15085-1079	1	65B15085-1061 RevHD	1440	46	-49	LN1032	Production	F18.6	-	-	
65B15085-79	1	65B15085-1061 RevHD	1440	32	-90	LN1039	Production	F18.6	-	-	
65B15085-80	1	65B15085-1061 RevHD	1440	33	-90	LN1039	Production	F18.6	-	-	
Funct Test		FT1W15085-0103Rev B				LN1027					

The module shown in Figure 5.7 is rich with characteristic data. Although the module does not physically contain the engineering specification, its characteristics “point” to the physical single source of the engineering specification. Recent advances in relational

database technology allow part characteristics²¹ to play a powerful role in this new configuration specification process including information which has been previously maintained on the drawing picture sheet. By moving this information off of the picture sheet and into a relational database, the data can be made available to all users from a single and sole authority data source. This should improve data accuracy while reducing the effort required to maintain design and production data.

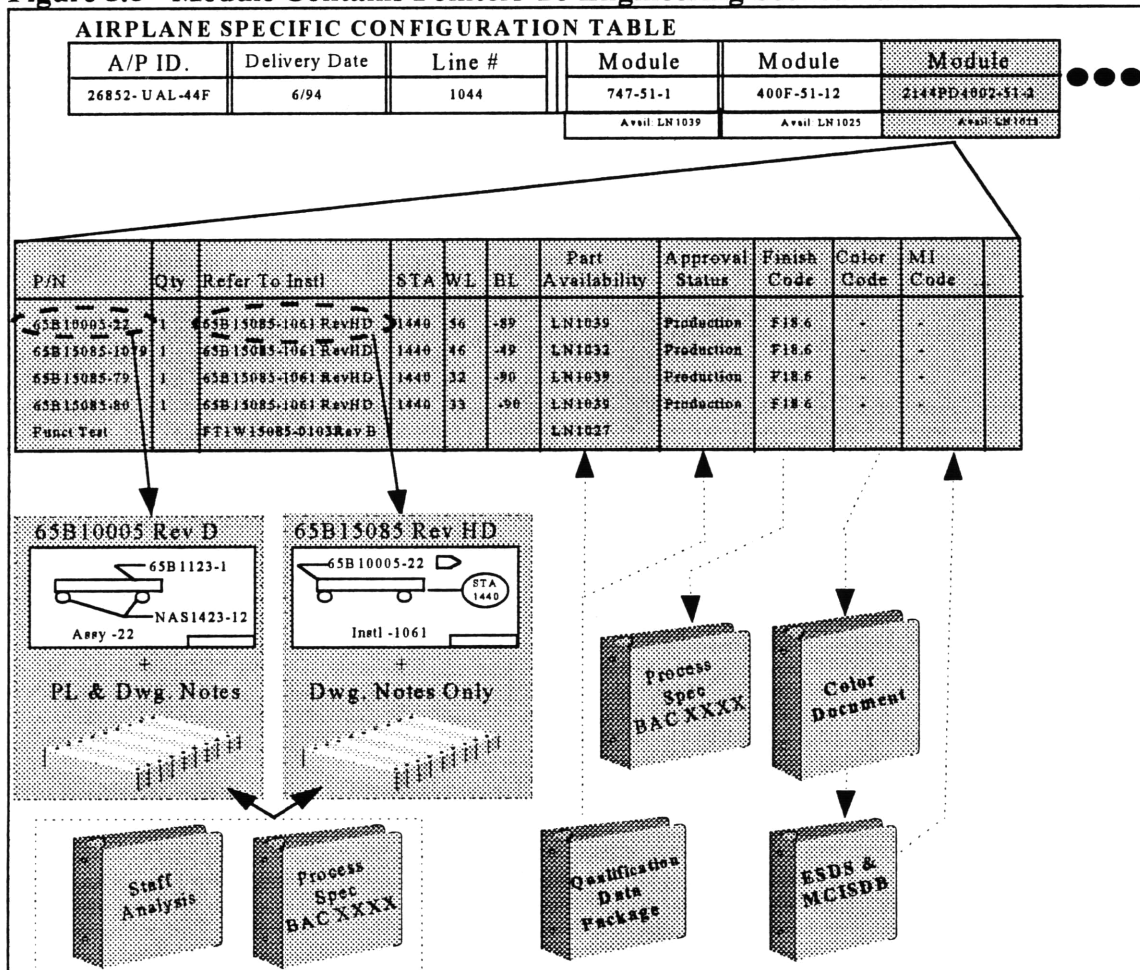
Module Characteristics Point to Sources Of The Engineering Definition - Module characteristics include material type, process specifications, color, certification status. As discussed earlier, the module is not the source of the engineering definition, but list characteristics data which “point” to the source for the engineering definition. This concept is shown schematically in Figure 5.8.

Figure 5.8 shows the Airplane Specific Configuration Table (originally derived from the Customer Specific Option Selection Table) and include the 2144PD4002-51-2 module. This module contains four part instances and one functional test instance. Consider the first part instance shown in the module. The “part instance” of interest is the 65B10005-22 assembly. Figure 5.8 shows that the 65B10005-22 assembly is defined by an engineering assembly drawing. Also contained in the drawing is the part list for the assembly and drawing notes reflecting process specification information and unique features. The 65B10005-22 assembly contains a part quantity, and a “refer to installation” descriptor. It is the 65B15085-1061. Therefore, the 65B10005-22 assembly inherits its part instance from the location information contained in the 65B15085-1061 drawing. The installation is defined by the drawing shown in Figure 5.8 and drawing notes shown in Figure 5.8 as well. When the -22 assembly activates the -1061 installation, it activates not only the location information of the part instance, but all applicable drawing notes and process specifications that are contained in that particular drawing.

²¹ Part characteristics or descriptors are often referred to as data characteristics when in the context of data base design and object oriented programming. In this thesis, characteristic or descriptor data is defined as data about the part or object of interest.

It should also be noted that in the new configuration process, **the installation drawing does not contain a parts list**. The source of the physical design configuration specification is solely provided by the module. Figure 5.8 also shows the relationship between the drawing definition and process specifications, and staff analysis required to properly fabricate and certify the part instance.

Figure 5.8 - Module Contains Pointers To Engineering Source Data



In addition to assembly and installation drawing characteristics of the part instance, physical location, part availability, approval status, color, and MI (material identifier) characteristics are also part of the module. Physical part location is inherited by the part

instance from the installation drawing. Since the parts can already be uniquely identified by the drawing, the location characteristics are optional in this case.

Part availability is derived from the Engineering Change that creates the part. The Engineering Change defines the airplane line number (or calendar date) for which the first part will be available to support. Any aircraft constructed on or after the “availability line number” for the part instance may be equipped with the part. Part availability descriptor guarantees that tool and plans are available to support fabrication.

The next characteristic in the module reflects the approval status which is derived from the part qualification and test and data package. Approval status declares whether the part is a fully qualified production part or if it is a part that has special limitation placed upon it (e.g. special inspection, limited life etc.). Approval status also points to the document that establishes the source of the approval.

The Finish Specification descriptor reflects the finish type applied against the part. The code F18.8 is defined in the company’s process specifications. This information is usually contained in the parts list to the engineering drawing. By removing this information from the engineering drawing parts list and moving it into the module, structured queries may be used to search for parts with a common set of characteristics by operating against the descriptor data directly. This simplifies and reduces the effort to manage the engineering data. For example, an airline customer could request a list of all parts on his airplane that use the anti-corrosion zinc undercoat. This query could be easily implemented by operating on the Finish Code part descriptor data contained in the module thereby eliminating the need to manually interrogate all of the drawing sheets for that customers airplane.

Color codes represent the next characteristic. These are especially important for interior parts because of the potential for fire and smoke inhalation in the cabin. If a part contains color, the color code field will assign one of the approved color codes contained in the

color document. Once color codes are specified, MI (Material Identifier) codes are established. Material identifier codes are used to identify the applicable certification tests (flame, smoke, heat) which qualify a particular part for use in the interior of the aircraft. MI codes are applied to a part instance only after the color codes have been established. Color codes point to the color document. The sole specification are then processed by the ESDS/MCISDB expert system (Boeing internal software) which retrieves the appropriate FAA approved certification test. By maintaining this data as an a characteristic to the part, queries can again be implemented to simplify engineering data management problem.

Module Characteristics Expanded to Include Manufacturing Data - The fundamental relationship between the physical design configuration specification and the physical production configuration specification manifests itself as manufacturing characteristics against the part instance. The engineering characteristics described in Figure 5.8 have been expanded to include the manufacturing data. Manufacturing data is applied against each part as is shown in Figure 5.9. As before, these characteristics are not the physical manufacturing definition but “pointers” to the authority for the production activity, including procurement code and a host of work instruction related information such as job numbers, control codes, plan numbers, and tools.

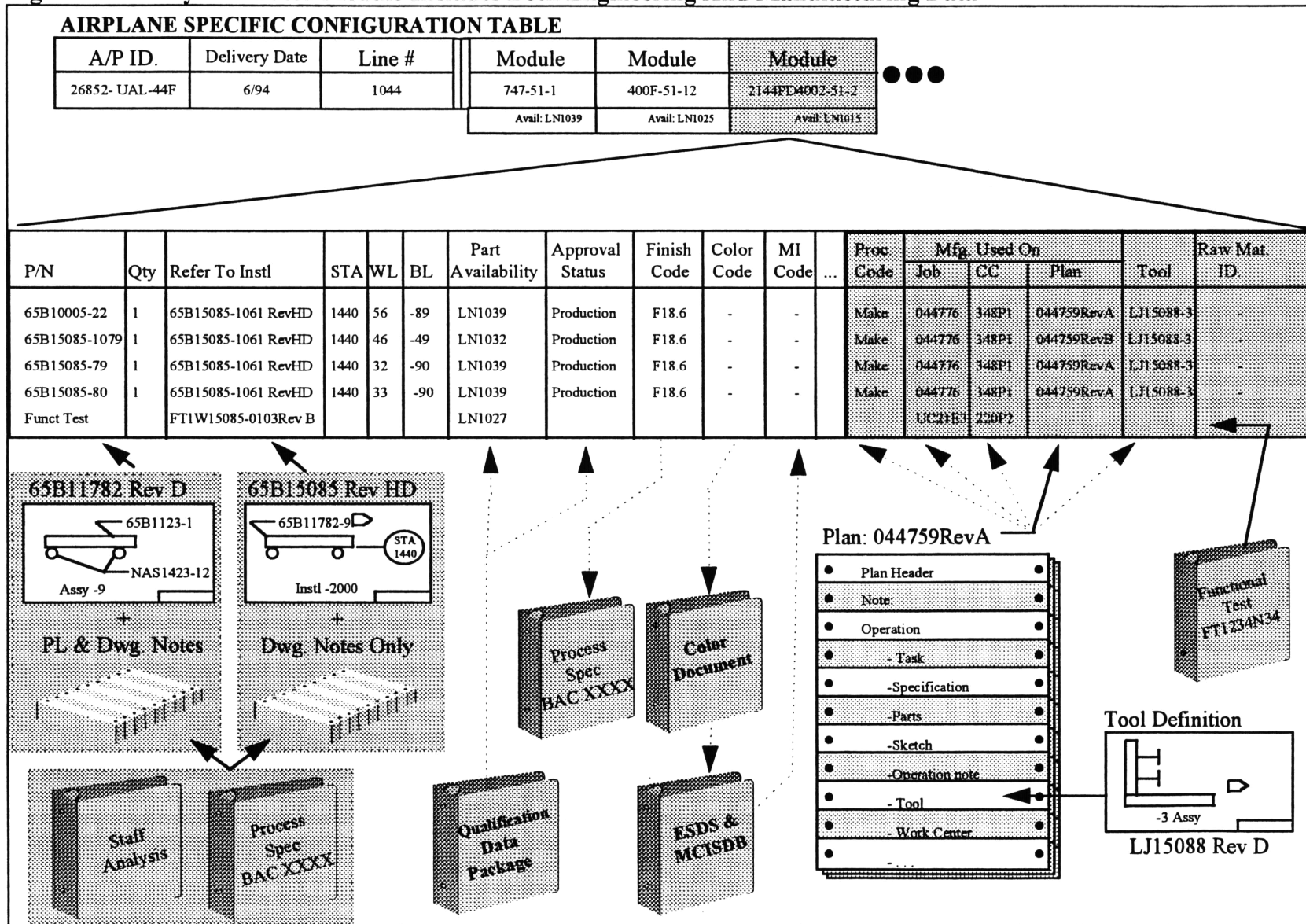
The procurement code characteristic identifies whether the part is made internally or contracted outside the corporation. This entry allows queries to determine the number and type of parts that are currently being procured outside the organization.

Other manufacturing related characteristics include the job number, control code and plan. The job number describes the actual work instructions distributed to the factory floor which is necessary to fabricate or assemble the part. The control code (CC) describes the physical factory location where the work is accomplished. The plan identifier contains the revision level of the source control file that was used to issue the jobs. Figure 5.9 shows that the job, control code and plan are “pointers” to the physical plan. The physical plan contain the actual instructions and is the authority for factory operations. By underlying

this information with the part instance, the relationship between the option (functional configuration), and all of the locations in the factory where work is performed to support that option becomes visible. This visibility supports the reduction in cycle time showing which work instructions must be re-routed to create the manufacturing streams which will drive the installations of the options to the last stages of the fabrication process.

Tooling characteristics are also included. Tool usage is described in the plan. Again, by aligning tool usage by part instance, the full impact of moving work between control codes can be more easily understood. The characteristics described in this section are merely a subset of the total set of characteristics which are implemented in a production environment. This list is not intended to be complete but to identify some of the essential characteristics which are required to align the Functional Configuration Specification with the Physical Design Configuration Specification with the Physical Production Configuration Specification.

Figure 5.9 - Fully Attributed Module Includes Both Engineering And Manufacturing Data



5.4 Phase Four: Re-Engineering To Reduce Cycle Time

After aligning the configuration specifications between the functional design, physical design and the physical production, it is possible to re-engineer the engineering design to significantly reduce cycle time. Today, the BLGS Bulkhead has a cycle time equal to 875 days (almost 2 1/2 years). By aligning the physical design configuration specification with the functional configuration specification it was possible to identify changes to the engineering definition which reduce the cycle time down to 131 days.

The module definition for the bulkhead is described in Figures 5.6. By expanding the part characteristics to include Re-Order Lead Time (ROLT), the cycle time for each customer selected option can be explicitly determined for the BLGS bulkhead. To demonstrate this process, consider the re-order lead time for the “Lower Lobe Cargo Bay Air Conditioning Option”. As described earlier, the Physical Design Configuration Specification for this option is defined by Module 2162PD4001-51-1. The physical contents of module are shown in Figure 5.10. By aligning the physical production with the physical design, each part instance inherits a re-order lead time characteristic from the manufacturing data. The order lead time characteristic is shown in Figure 5.10 for each part instance associated with the selection of the “Lower Lobe Cargo Bay Air Conditioning Option”.

Figure 5.10 shows that relative to the BLGS bulkhead, the cycle time required to implement the “Lower Lobe Cargo Bay Air Conditioning Option” is driven by only one part: the bulkhead web detail. The bulkhead web must be ordered 875 days prior to shipment. This requires that an airline customer must decide 2.4 years prior to shipment whether they will need air conditioning in the lower lobe of the cargo bay. The alternative course of action is to re-work an existing design in the intermediate stages of production.

Figure 5.10 - Order Lead Time Revealed For Every Part Instance In The Module

AIRPLANE SPECIFIC CONFIGURATION TABLE											
A/P ID.			Delivery Date			Line #			Module		
26852- UAL-44F			6/94			1044			747-51-1		
									400F-51-12		
									2144PD4002-51-2		
									Avail: LN1039		
									Avail: LN1025		
									Avail: LN1015		

P/N	Qty	Nomenclature	Refer To Instl	STA	WL	BL	Part Availability	Part Approval Status	Finish Code	MI Code	Order Lead Time
144U2007-2	1	Stiffener	65B15085-1062 RevHF	1480	176	97	LN1039	Production	F18.6	-	42 Days
65B10005-23	1	Web, Bulkhead	65B15085-1062 RevHF	1480	56	89	LN1039	Production	F18.6	-	875 Days
65B15085-218	1	Bracket, Stabilizing	65B15085-1062 RevHF	1485	117	119	LN1032	Production	F18.6	-	21 Days
65B11985-4	1	Web, Cargo Beam	65B15085-1062 RevHF	1485	119	49	LN1039	Production	F18.6	-	131 Days
BACB30NZ8	1	Fastener, HI-LOK	65B15085-1062 RevHF	1485	117	11	LN1039	Production	F18.6	-	1 Day
BACB30NZ6	1	Fastener, HI-LOK	65B15085-1062 RevHF	1485	117	13	LN1039	Production	F18.6	-	1 Day
Funct Test		Leak Check Cert.	FT1W15085-0103Rev B				LN1027	-	-	-	-

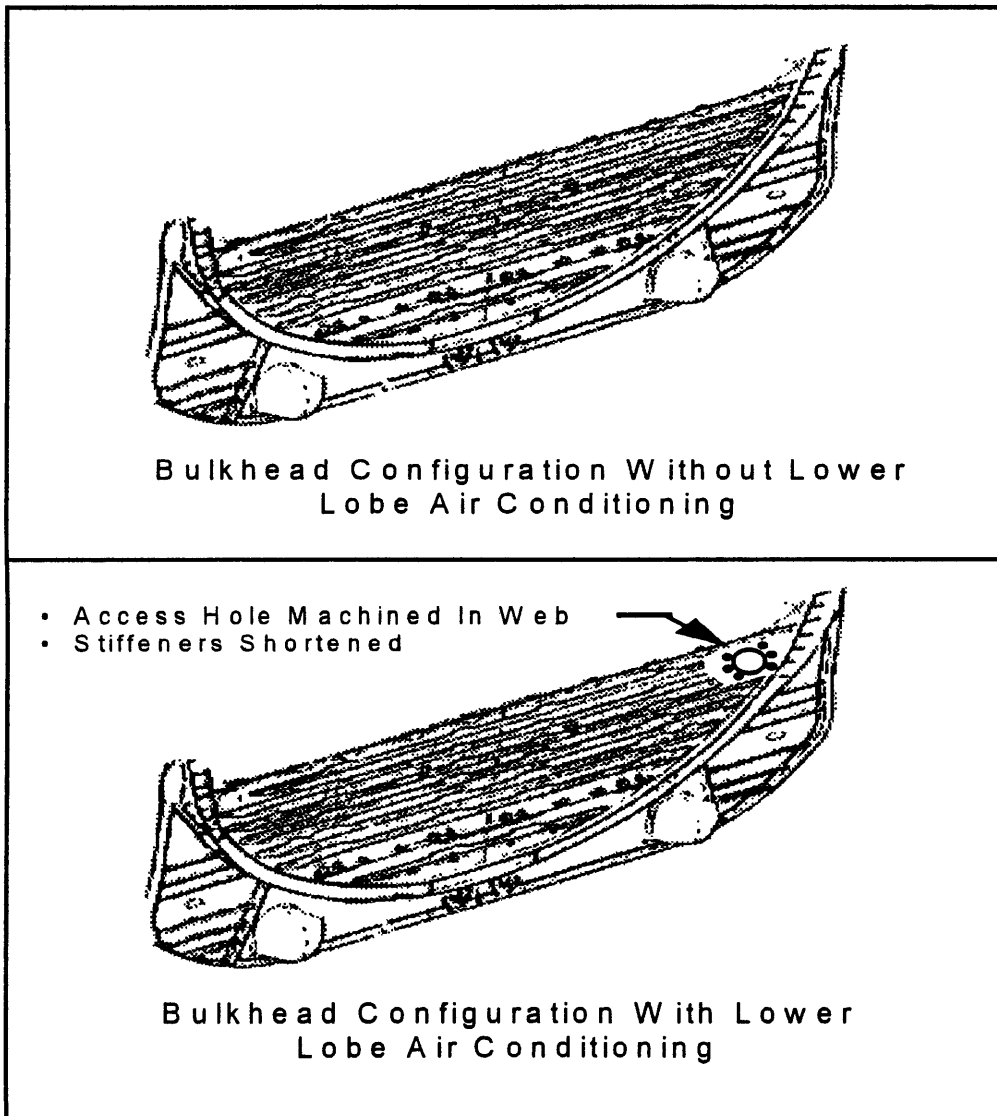
“Once You Know What Needs To Be Re-Designed, The Re-Design Is Easy” - By aligning the functional configuration specification to the physical design and physical production specifications using options, modules, and fully defined part instances, lead time analysis explicitly determines which engineering part instances must be re-engineered. In the case of the BLGS Bulkhead, the bulkhead web is the driver for lead time analysis. In the current design the web is uniquely configured to support either the air-conditioning, and or heating hardware. The bulkhead is a long lead item for very good reasons. It is a machined and chemical milled to close tolerances required by the design. After chemical milling, it is shot peened to improve its fracture toughness. After fabrication of the web is complete, it is the first detail part placed in the assembly tool. Basically, all the other stiffeners and brackets cannot be installed until the bulkhead web is fabricated and loaded into the assembly tool.

Since processes that surround the fabrication of the web are inherently serial and time consuming, lead times for the bulkhead are not reduced by process/design technology, but by redesigning the bulkhead so that it can be customized in the last stages of fabrication process thereby dramatically reducing the lead time between customer specification of the

option selection and delivery of the aircraft. To accomplish this, the configuration of the web must be standardized so that it can be used on all models and options.

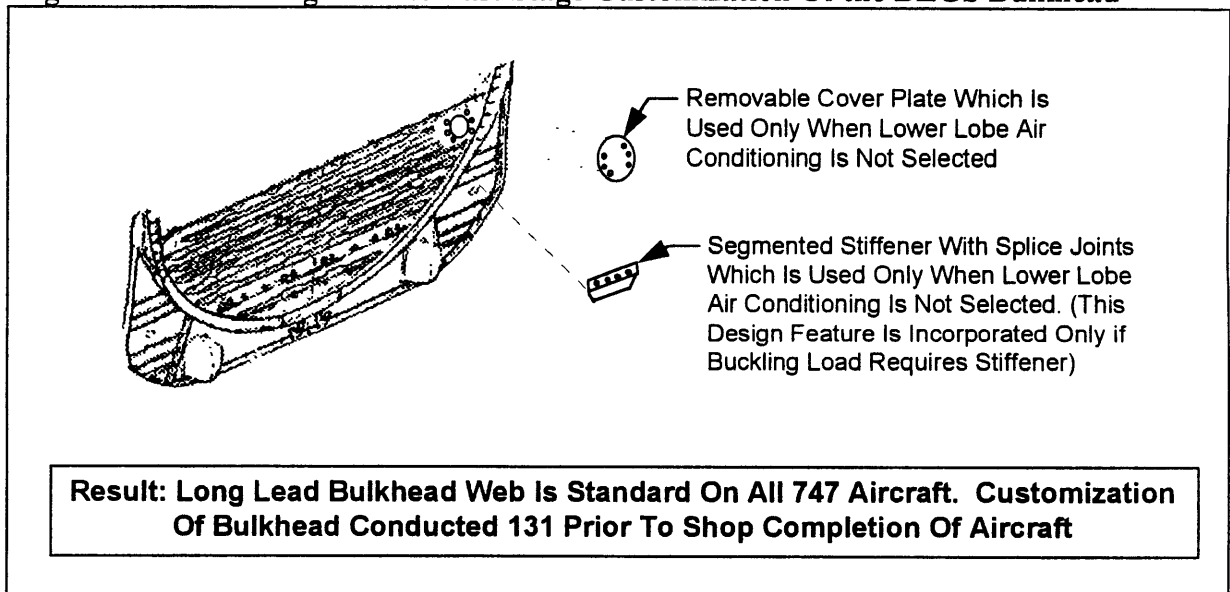
The current design of the bulkhead web adds a 8.75" diameter hole at water line 176" and buttock line 175" only when the customer selects the lower lobe air conditioning option. The hole must be machined into the web detail early in the fabrication process to support shot peen requirements. If the customer does not select the air conditioning, the web is machined without the hole. (See Figure 5.11)

Figure 5.11 : Bulkhead Web Configuration Altered By Incorporation Of Lower Lobe Air Conditioning Option



In an effort to standardize the configuration across all 747 aircraft, the web design can be altered to incorporate the hole in bulkhead design for all aircraft configurations. To accomplish this, a companion cover plate and segmented stiffener designs are developed for installation when the customer does not desire air conditioning as is shown in Figure 5.12. This physical modularization of the design allows the bulkhead to be fabricated in a single configuration for all 747 customers. The 875 day lead time required for the bulkhead web is moved out of the “Lower Lobe Air Conditioning Option” and into the “747 Major Model Option”. This moves the long lead item hardware out of option streams which are highly variable (See Figure 4.7) and into option streams which are stable and accurately forecasted. By moving long lead hardware into option streams which are less variable, forecast reliability is improved thereby reducing inventory requirements to meet drastically reduced cycle times.

Figure 5.12 - Re-Design Allows Last Stage Customization Of the BLGS Bulkhead



By moving the web out of the air-conditioning module and into the 747 major module, the cycle time for both the cargo bay air conditioning option and the cargo bay heater option can be reduced from 875 days to 131 days.

This analysis was applied only to the BLGS Bulkhead. However, by aligning all of the physical designs around the functional configuration specifications, lead time analysis can be used to re-engineer structure, interiors, systems, avionics, and wiring by providing clear visibility into critical hardware for any option or combination of options. The module characteristic data will also define the control code location where each part instance is installed. This information will become invaluable for redesign of the manufacturing sequence to delay customization of the aircraft thereby dramatically reducing cycle times.

6.0 IMPACT TO THE ENGINEERING DRAWING SYSTEM

The module based product architecture makes significant changes to the engineering drawing system. Aside from eliminating effectivity from the product structure, this new architecture provides an opportunity to parametrically configure designs “off the drawing picture sheet” thereby increasing design re-usability while reducing engineering drawing maintenance costs.

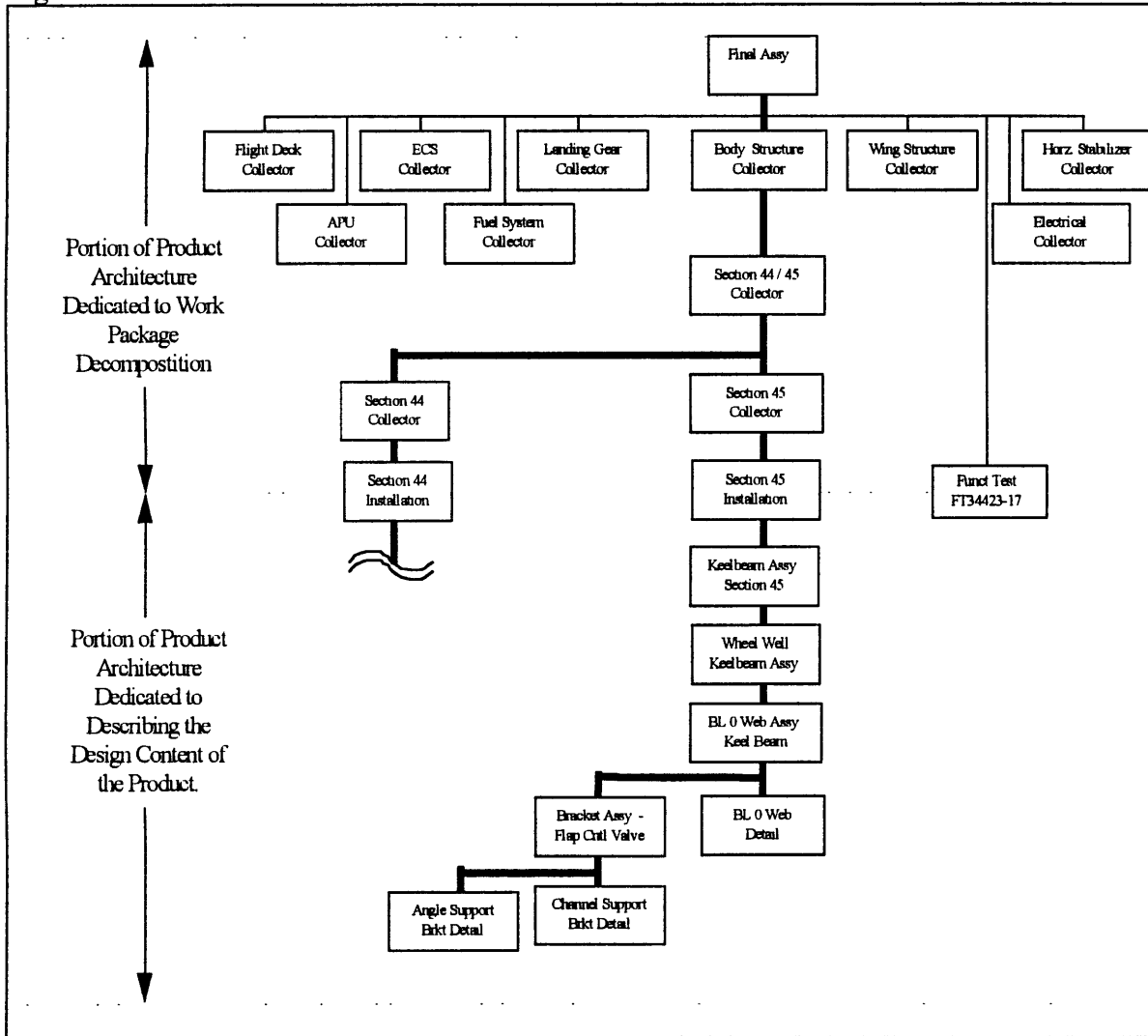
6.1 Traditional Engineering Drawing Structure Must Be Modified To Support The Module Based Configuration Specification.

Today’s existing drawing system uses effectivity to “internally limit” the usage of a part in assemblies and installations (see section 3.2 for a detailed explanation of effectivity). The module based product architecture eliminates the use of effectivity by moving to a “pure part number control” methodology in order to maintain configuration accountability.

Traditional Engineering data architectures are typically derived from the drawing tree. These data architectures are usually defined by final assembly, collector, installation, sub-assembly and detail drawings. Traditional drawing trees have two primary purposes. First, to decompose the aircraft into manageable work packages. Second, to define assembly relationships between discrete detail parts, sub-assemblies, and major assemblies. A typical drawing tree is shown in Figure 6.1. At the top of the drawing tree are families of collector drawings which establish the functional decomposition of the aircraft. Categories for functional decomposition includes Wing Structure, Body Structure, Landing Gear, Horizontal Stabilizer, Electrical and Electronic, Fuel System, Environmental Control System, Auxiliary Power Unit, and Flight Deck. These drawings do not contain picture sheet information. They are used primarily to define work packages, and collect miscellaneous parts in the drawing parts list. They are a fundamental part of any configuration accountability process which uses effectivity to define and control the aircraft configuration. Below the collector drawings are

installation, assembly, and detail part drawings which completely define the engineering and process specifications of the product. Installation, assembly, and detail part drawing are different than collector drawing because they usually contain picture sheet/geometry information in addition to the parts list.

Figure 6.1 - Traditional Product Structure for Commercial Aircraft.



Traditional product structures for commercial aircraft are often characterized as “deep” structures in that they are organized in hierarchical structures composed of many levels of drawings. These structures typically contain anywhere from 6 to 16 levels. Effectivity based configuration management processes, maintain configuration accountability in these

deep product structures by placing exception notes on the drawing picture sheet. These exception notes act to internally customize the part or assembly without changing the drawing or part number. This procedure obscures the physical content of any part number used in production. (A single part number may have several configurations because the exception notes shown on the picture sheet customize the configuration for a particular airplane or set of airplanes.) Using effectivity to internally re-configure part numbers complicates the configuration accountability process. This requires reconciliation of exception notes against part numbers throughout the entire product structure in order to determine the actual configuration of any single customer's aircraft. The end result: assembly and installation part numbers no longer represent unique configurations of parts and manufacturing processes. This issue is particularly frustrating for Boeing Customers who order spare parts by part number identifiers and may not get the parts that they need.

To eliminate these problems, the module based product structure implements a "pure part number" control methodology. Pure part number control dictates that part numbers have one and only one unique configuration. Therefore, any design change which alters a part's form, fit, or function must re-identify the original part and all affected major and minor assemblies up to the point of interchangeability. This method of configuration identification and control uniquely identifies each part on the aircraft thereby greatly simplifying configuration management and accountability processes.

Although pure part number control simplifies identification of the configuration, it creates a significant number of part number changes when applied to deep, hierarchical drawing structures. Boeing's deep drawing structures make pure part number control difficult to implement and sustain. For example, assume that the "BL 0 Web Detail" (shown in Figure 6.1) is re-designed using pure part number control procedures. After re-identifying the "BL 0 Web Detail, pure part number control requires that the "BL 0 Web Assembly", "Wheel Well Keelbeam Assembly", "Keelbeam Assembly Section 45", "Section 45 Installation", "Section 44/45 Collector", "Body Structure Collector" and the "Final

Assembly Drawing” also be re-identified. Therefore, in order to implement pure part number control, the hierarchical drawing structure must be fundamentally restructured.

6.2 Module Based Product Architecture Creates A Flat Product Structure Enabling Pure Part Number Control

The module based product architecture aligns the functional configuration specification to the physical design configuration specification by grouping fully characterized parts into modules which have an explicit relationship to the option which configures the module to an aircraft. This alignment allows significant restructuring of the product architecture thereby enabling pure part number control. The product architecture can be restructured in two major ways: (1) elimination of collector drawings, (2) reorganization of the installation drawings.

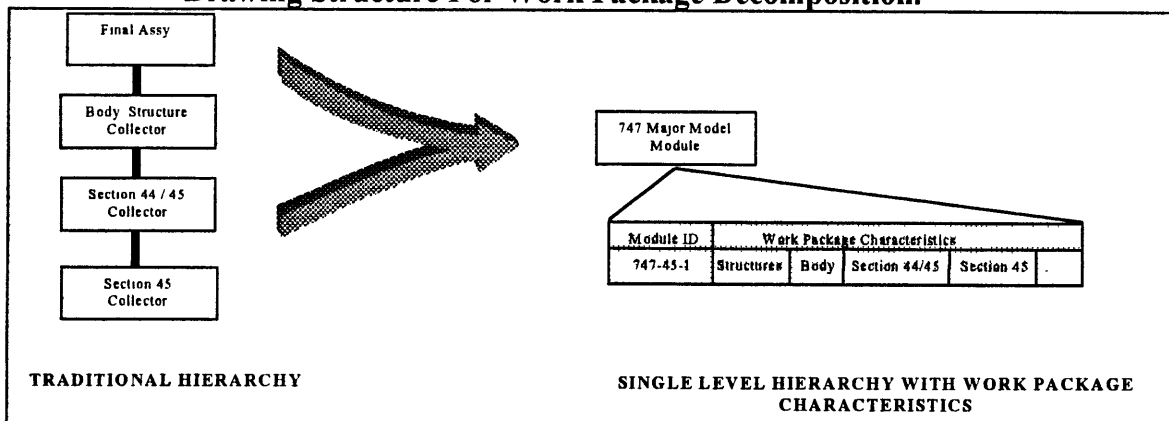
Collector Drawings Are No Longer Required - As described earlier, collector drawings assign effectivity against all major assemblies and decompose the aircraft into manageable work packages. Modules eliminate the need for collector drawings in two ways. First, modules eliminate effectivity from the product structure using the Aircraft Specific Configuration Table to configure the airplane by customer option. Second, modules contain data about themselves which is used functionally and physically decompose the aircraft into work packages.

For example, consider the major model module. This module contains over 50,000 parts. In order to manage all of this information, the 50,000 parts must be decomposed into smaller, manageable work packages. In order to accomplish, the module contains work package characteristics which allow the 50,000 parts in the major model to be divided up by the design organization responsible for maintaining the design. An example of a module containing typical work package characteristics is shown in Figure 6.2. Traditional methods for decomposing the aircraft into work packages used collector drawings as is shown on the left side of Figure 6.2. In this example, the work package decomposition is accomplished by characteristics data contained in the module. These

characteristics describe the function and physical characteristics contained in this subgroup of the major model module. These characteristics includes: Aircraft Structures (functional decomposition), Section 44/45 major assembly (end item decomposition of the middle fuselage near the wing), Section 45 assembly (end item decomposition of fuselage aft of wing). It should be noted that these decompositions are imbedded in the drawing tree and are maintained manually.

Modules can decompose the aircraft into work packages by storing characteristics about the module in an electronic database. A module based work package decomposition is shown on the right side of Figure 6.2. The module based decomposition creates a single level hierarchy that separates work packages by functional discipline and end item. In order to determine the contents of a single work package, an electronic query would be used to identify all modules that contain the desired work package characteristics. For example, the 747 major model module work packages characteristics include “Structures” followed by finer grain decomposition’s which include “Body”, “Section 45/44”, and “Section 45”. A query can be generated to collect all modules that are involve the “Structures” or “Structures + Body + Section 45” work packages. The relevant modules and engineering, planning and inspection data parts could be retrieved. These work package characteristics can be configured to produce the same work package grouping that currently exist in the traditional system. However, these work packages are based on module characteristics which are stored in an electronic database.

Figure 6.2 - Modules With Work Package Characteristics Replace The Collector Drawing Structure For Work Package Decomposition.

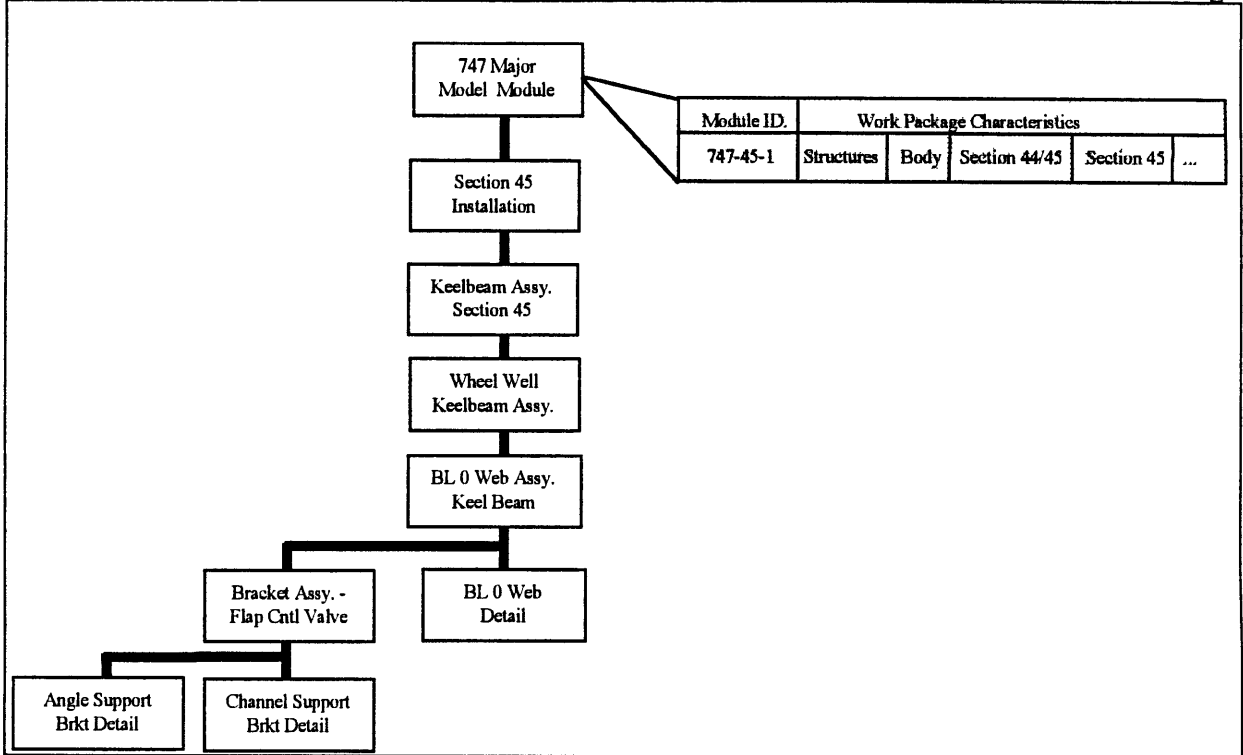


By physically maintaining this data in an electronic database, structured queries may be electronically performed which allow modules to be sorted by: functional area (Structures, Electrical & Electronic, Fuel System, etc.), major group (Body, Wing, etc.), physical end item (Section 44, Section 41 etc.) or any combination of these elements. Therefore, characteristic data at the module level (not at the part level) provide a method to functionally and physically decompose the airplane into work packages without creating drawing sheets and part numbers that must be manually maintained in a pure part number control environment. This minimizes the amount of labor required to maintain work package definitions as well as the number of part number rolls that would have resulted in a pure part number control environment.

It should also be noted that module characteristics used to define the work package can be modified as organizational influences dictate without modifying the drawing tree. For example, module characteristic data can reorganize work packages around product development teams or other emerging organizational forms without drastically altering the fundamental product structure used to configure the physical aircraft.

Eliminating collector drawings by implementing the module based product architecture significantly “flattens” the product structure. A typical result is shown in Figure 6.3. This example takes the product architecture presented in Figure 6.1 and implements modules to eliminate collector drawings. By eliminating collector drawings, the depth of the product structure was reduced from 10 levels to 7.

Figure 6.3 - Intermediate Drawing Structure With Modules Replacing Collector Drawings.



Reorganization Of The Installation Drawings - As noted above, eliminating collector drawings from the product structure reduced the depth of a typical drawing tree from 10 levels to 7 levels. Further simplification of the product structure is possible by reorganizing information at the installation drawing level. American Society Of Mechanical Engineers (ASME) Engineering Drawing Standard, Y 14.4, describe the requirements of an Installation Drawing. The Installation Drawing “provides information for properly positioning and installing items relative to their supporting structure and adjacent items. Requirements for installation drawing include (a) overall and principle dimensions in sufficient detail to establish space requirements for installation, operation, and servicing. (b) interface mounting and mating information. (c) interfaces for pipes and cable attachments. (d) information necessary for preparation of foundation plans including mount details. (e) References to interconnecting and cabling data and to associated lists. (f) identification of requirements for installation items not included in the parts lists of the using assembly drawing. (g) reference to assembly drawing of the major

item being installed. (h) a parts lists specifying the items to be installed. (i) supporting structure of associated items which are not included in the installed items may be shown.

In an effectivity based product structure, installation drawings contain effectivity exception notes located on the face of the picture sheet which alter the physical configuration of the parts and or processes. In order to determine the exact configuration of the product, the installation parts lists and picture sheet must both be reconciled against each other. Since exception notes alter the configuration with out changing the part number in the Engineering Bill of Materials, effectivity based systems require that the configuration authority for the aircraft be, both, the parts lists and the picture sheets. In a module based product architecture, pure part number control allows the Engineering Bill of Material to uniquely and completely specify the configuration. A part number represents one and only one unique configuration thereby eliminating the need to reconcile the parts list against the picture sheet. The installation drawing parts list becomes a view of all parts described by a particular drawing but the module defines the configuration by uniquely identifying all parts (using the part instance methodology described in section 4.1) that define the configuration. Since the Engineering Bill of Material is generated from the module, the parts list which normally accompanies an installation drawing only describes the parts shown in the drawing and is not the configuration authority for production.

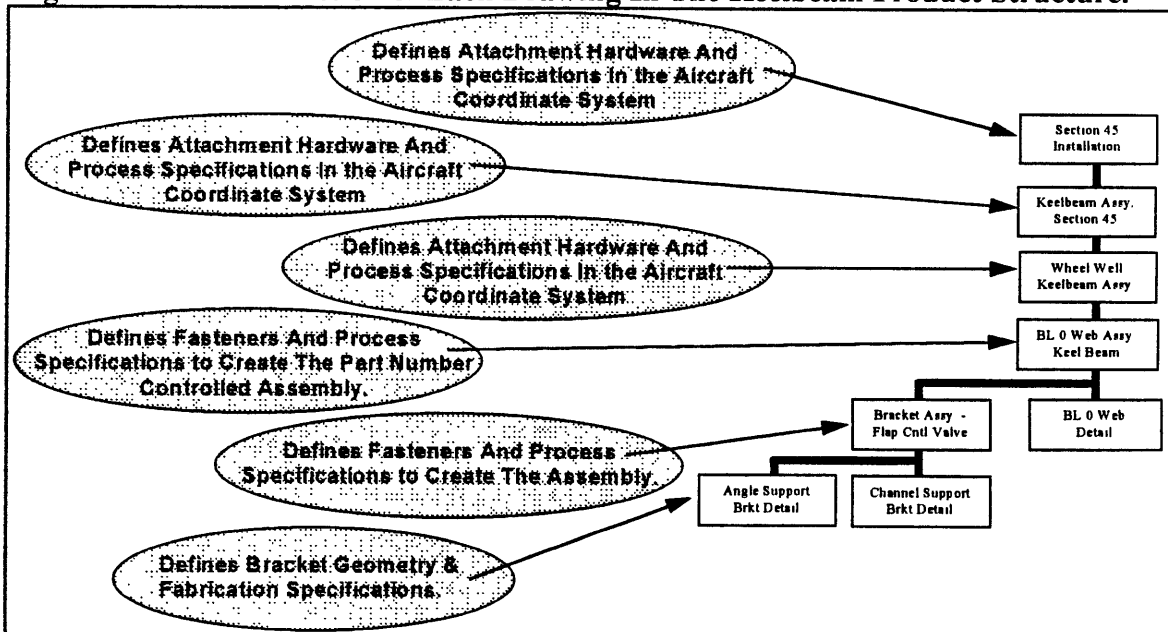
In a module based product architecture, the installation drawing serves three major functions: (a) locate parts and assemblies in the aircraft coordinate system, (b) define attachment hardware (c) define process specifications related to the installation activity. In the module based product architecture, installation drawings dash numbers and parts lists no longer define the configuration of the aircraft. Modules are the sole authority for the generation of the Engineering Bill of Material and the complete configuration specification of the aircraft.

Since modules define the configuration specification, the traditional drawing structure can be notably simplified. To understand this, consider the engineering definition for the

Section 45 Keelbeam shown in Figures 6.4. At the bottom of the assembly structure, detail parts for web and support brackets are defined. At the next level in the drawing structure, the Keelbeam web assembly is described. The Keelbeam Web Assembly drawing defines the stiffeners, chords, webs, brackets and fasteners required to create the web assembly end item. At the next level, the Wheel Well Keelbeam drawing joins the wheel well sub-assembly to the Keelbeam Assembly. The most important feature of this drawing is that it locates the major assemblies in the aircraft coordinate system thereby allowing the specification of the “part instance”. The next two drawings in the product structure are the Section 45 Keelbeam assembly and the Section 45 end item installation. Both of these drawings locate the parts in the aircraft coordinate system, define attachment hardware requirements and process specifications for the major assembly.

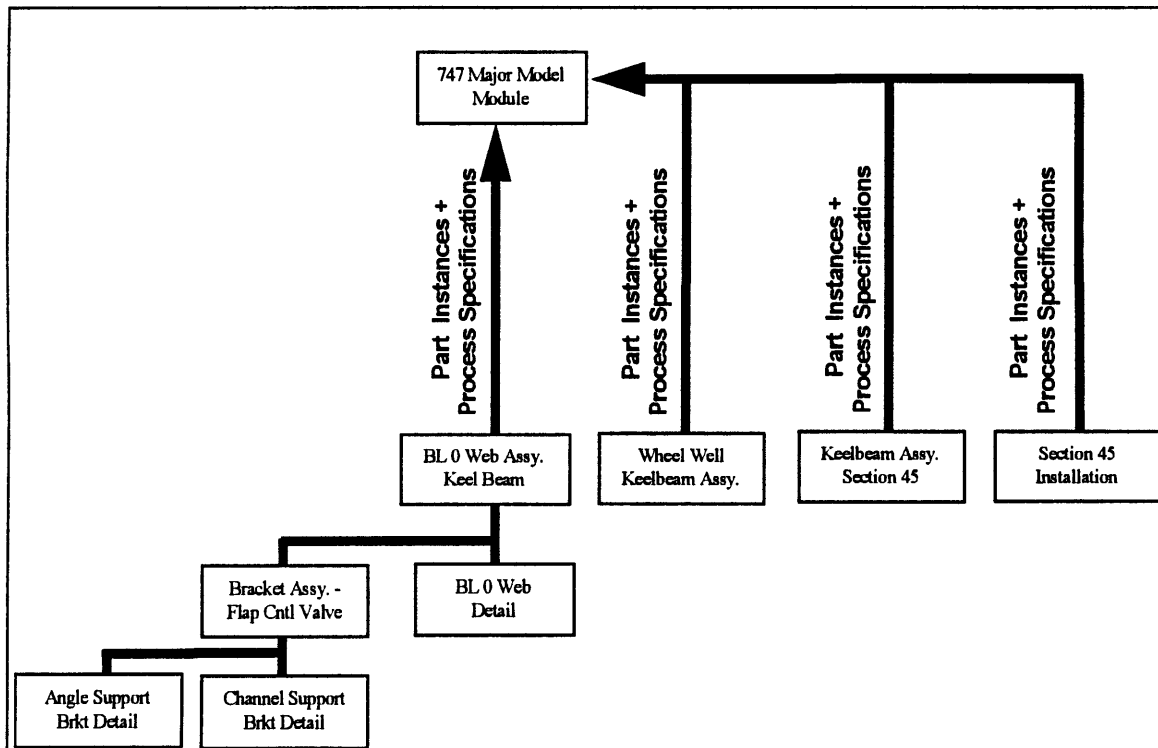
Each of these drawings provides unique definition for the Keelbeam with respect to the Section 45 end item. The definition provided by each drawing is summarized in Figure 6.4. Again, it should be noted that three of these drawings locate parts in the aircraft coordinate system. Drawings which locate parts in the aircraft coordinate system include the “Section 45 Installation”, “Keelbeam Assembly, Section 45”, and the “Wheel Well Keelbeam Assembly”.

Figure 6.4 - Basic Function of Each Drawing In The Keelbeam Product Structure.



Once parts are located in the aircraft coordinate system, modules can define the part instance and specify the configuration of the aircraft. Since the Section 45 installation, Keelbeam Assembly Section 45, and the Wheel Well Keelbeam Assembly drawings locate parts in the aircraft coordinate system, the module can uniquely identify each part instance and align these part instances with the options they support. Although the Section 45 Keelbeam Assembly and the Keelbeam Wheel Well Assembly are called assembly drawings, they are actually installation type drawings in disguise. The most important feature of each of these drawings is that they provide definition of the parts in the aircraft coordinate system. Modules configure the aircraft directly from these drawings thereby flattening the product structure. This fact allows the module based product architecture to reorganize the drawing structure as is shown in Figure 6.5.

Figure 6.5 - Module Base Product Architecture Significantly Flattens the Product Structure Greatly Simplifying Pure Part Number Control.



The module explicitly specifies the configuration by uniquely identifying all parts necessary to define the configuration. This eliminates the hierarchical product definition

between the Section 45 installation, Keelbeam Assembly Section 45, and the Wheel Well Keelbeam Assembly drawings. As is shown in Figure 6.5, part instances are created by listing specific part numbers and “refer to” installation drawings to locate and install these parts in the aircraft coordinate system.

This new product structure creates “part instances” as was described in section 4.1 This eliminates the ambiguity of having a part installed by several drawings which have been effectivity tabulated with exception notes. The end result is that parts are installed by one and only one drawing.

Summary - The module based product architecture eliminates collector drawings and modifies the hierarchical relationship between installation type drawings. These actions eliminate layers in the product structure and enable pure part number control. The drawing structure which was analyzed in this section is typical for most of the drawings found in commercial aircraft. In this example, the depth of the drawing structure was reduced from 10 levels to only 4. This allows the implementation of “pure part number” control by limiting the number of part numbers which must be re-identified when a part at the bottom of the product structure is re-designed.

6.3 Alternate Views Are Needed To Support Engineering Design

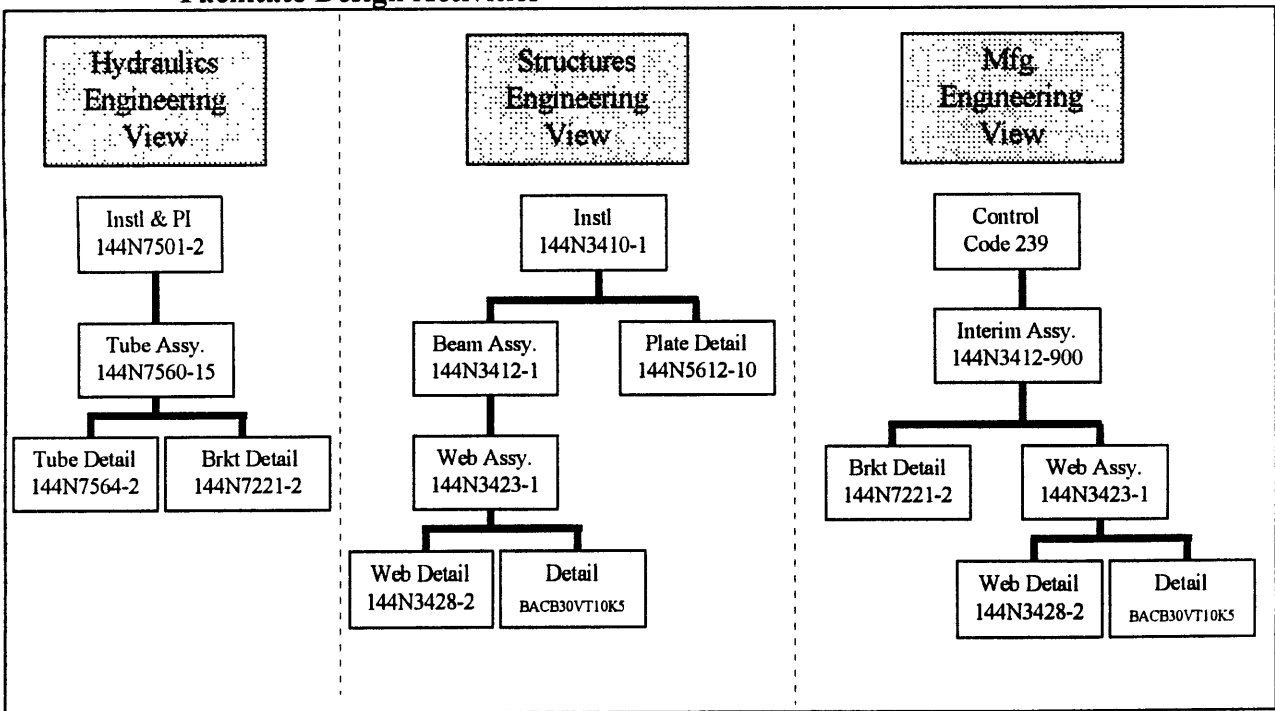
Although the module based product architecture provides a simplified method to control the configuration of commercial aircraft, alternate views are required to facilitate the engineering design and manufacture of the product. Engineering design requires functional views of the aircraft to allow necessary technical analysis (stress, aerodynamics, fire safety, emergency egress, etc.). For example, the Structural Design Engineer needs a view of the aircraft structure in order to determine load paths. The Hydraulic Systems Design Engineer needs a functional view of the hydraulics system to insure that all hydraulic circuits meet system level requirements and safety related separation

requirements. Manufacturing Engineers need a view of the manufacturing build sequence to insure that factory workers have adequate room to work efficiently.

Each engineering discipline has a set of functional views that must be maintained.

Functional views dictate the types and number of engineering drawings that are produced inside the product architecture. The module groups the parts defined in these drawings around the options they support. The modules are independent of the functional views. Figure 6.6 describes a typical set of engineering drawings which have been designed to provide the necessary views described above. This Figure shows not only the hydraulics and structures view, but the manufacturing “as-built” view as well. Note that the manufacturing engineering view contains an interim assembly that is a hybrid of the hydraulics assembly and the structures assembly. These assemblies are often known as -900 manufacturing assemblies and represent interim states of the product prior to completion of the aircraft.

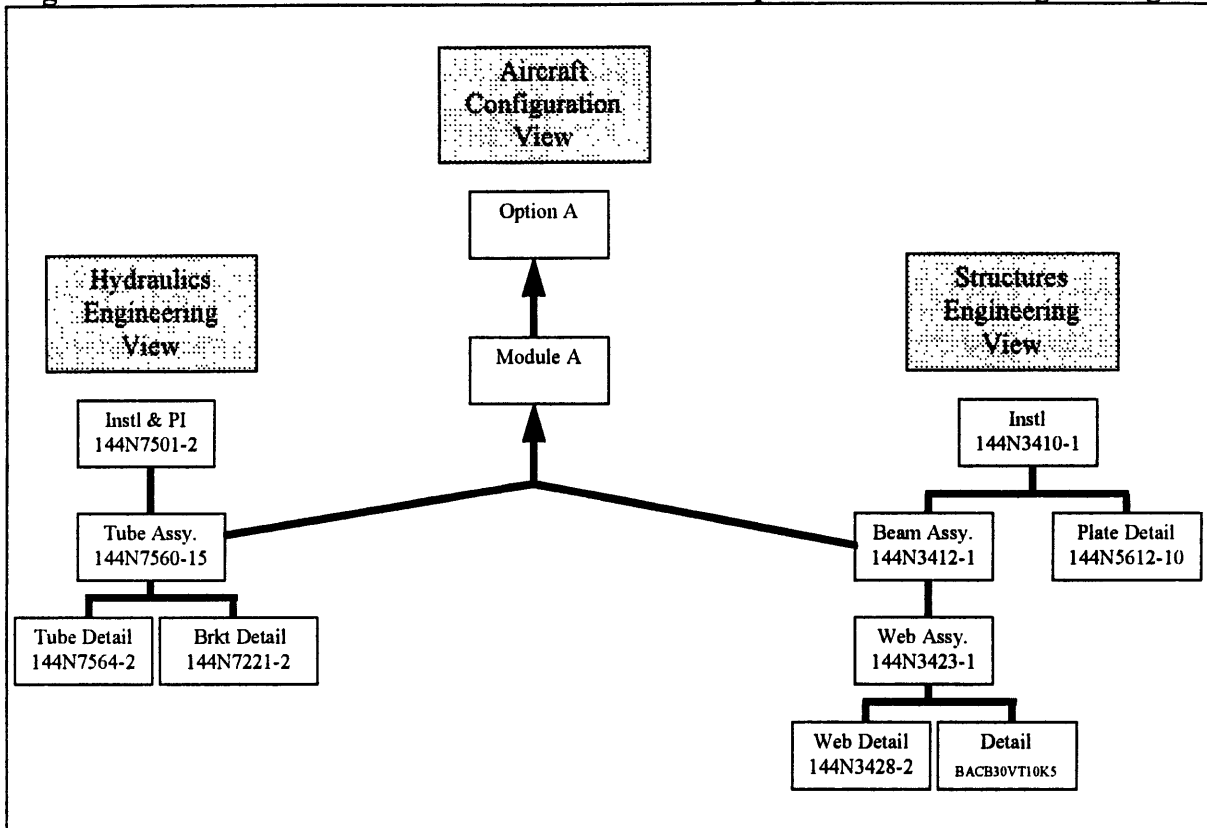
Figure 6.6 - Engineering Functions Require Unique Views Of The Product Structure To Facilitate Design Activities



By defining fully characterized parts inside the modules, part data is maintained in a relational data base with relationship maps which allow the creation of the necessary functional views. In addition, parts which are used in -900 assemblies can be reconciled against the engineering view electronically. The need to develop specific views in addition to the aircraft configuration view does not constrain configuration specification using the Module Based Product Structure. Engineering functional views determine the types of drawings that will be necessary to conduct design activities. Modules align the parts (defined in these functionally oriented drawings) with the customer selected options they support. The module based product architecture is independent of the functional view and does not constrain the development of these views. It does however suggest that the engineering view should push part location information (relative to the aircraft coordinate system) down in the product structure in order to simplify the product architecture used to configure the aircraft.

The module configuration view and the engineering functional view are related to one another through the part instance. The module identifies parts instances. Each part in the module refers to the drawing which locates the part in the aircraft coordinate system and define process specifications. To emphasize this point, the “Structures View”, “Hydraulics View” and “Configuration View” have been overlaid in Figure 6.7. The Tube Assembly (144N7560-15) and the Beam Assembly (144N3412-1) are identified in Module A which directly supports Option A. The Tube Assembly (144N7560-15) refers to the Tube Installation drawing (144N7501-2) for tube location and process specifications required to installation of the tube assembly in the aircraft. Likewise, the Beam Assembly (144N3412-1) refers to the Beam Installation drawing (144N3410-1) to locate the Beam and define process specifications related to the installation of the beam on to the aircraft. As can be seen, these views are highly compatible.

Figure 6.7 - Model Based Product Architecture is Compatible With The Engineering Views



6.4 Module Based Product Architecture Supports Hardware Variability Control Initiative

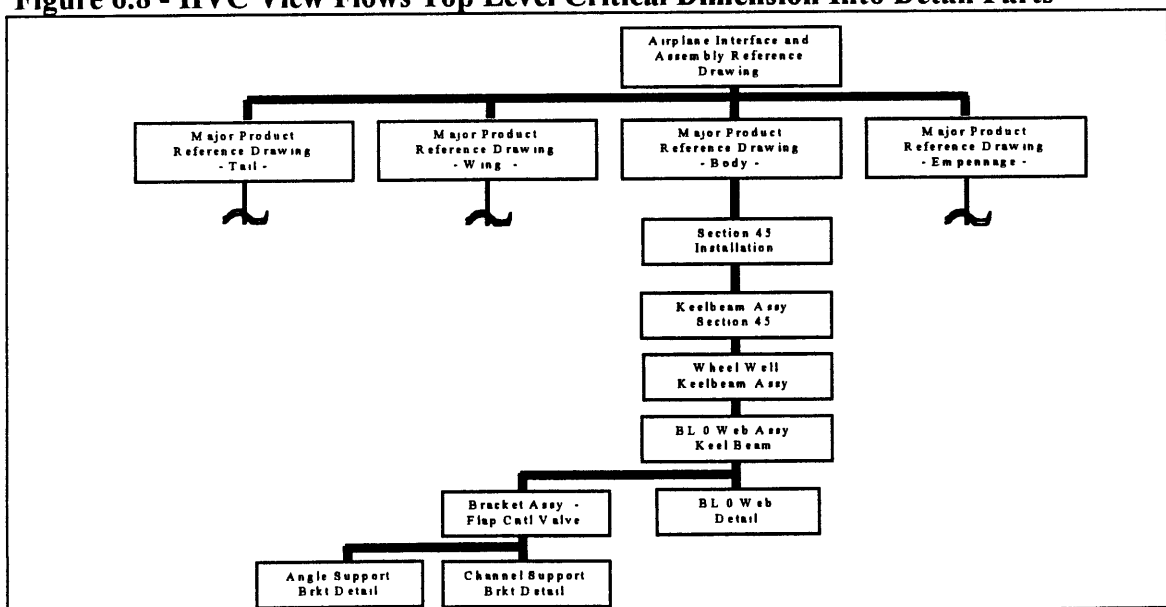
Another view of particular interest is the Hardware Variability Control (HVC) view of the aircraft. This view seeks to implement some form of Statistical Process Control (SPC) on critical part/assembly dimensions which significantly affect manufacturing cost and/or cycle time. Critical part/assembly dimensions are identified using a top/down approach. First, critical dimensions are defined for global features found on the completed aircraft (e.g. wing sweep, dihedral). Second, analytical procedures are used to identify the critical dimensions located on supporting sub-assemblies and detail parts. These critical dimensions are commonly referred to a “Key Characteristics” of a part or assembly.

To implement Hardware Variability Control, a unique view, similar to an engineering functional view, of the product structure is required. The typical Hardware Variability Control Key Characteristics are defined in an assembly features tree. This view typically

begins with the “Airplane Interface and Assembly Reference Drawing” which defines top level critical dimensions for the aircraft (e.g. wing sweep, dihedral). This drawing is a reference drawing because it does not physically define or build any parts, it serves as a device to collect SPC measurement data. Below this drawing are the “Major Product Reference Drawings”. These drawings establish the critical dimensions for each of the major products. Major products include wing, body, tail, & empennage. Again, these drawings are reference drawings because they do not physically define or build any parts, they are simply used to define dimensions of interest so that SPC data may be collected. Below the Major Product Reference Drawings are the Engineering installation drawings. These drawing are the authority for the product definition. Dimensions which have been determined as the “Key Characteristics” at the installation level are identified with notes on the picture sheet of the drawing. These notes tell the manufacturing engineer to conduct data collection when the part is installed in the aircraft. The manufacturing engineer creates work instructions which authorize the factory employees to collect the necessary data.

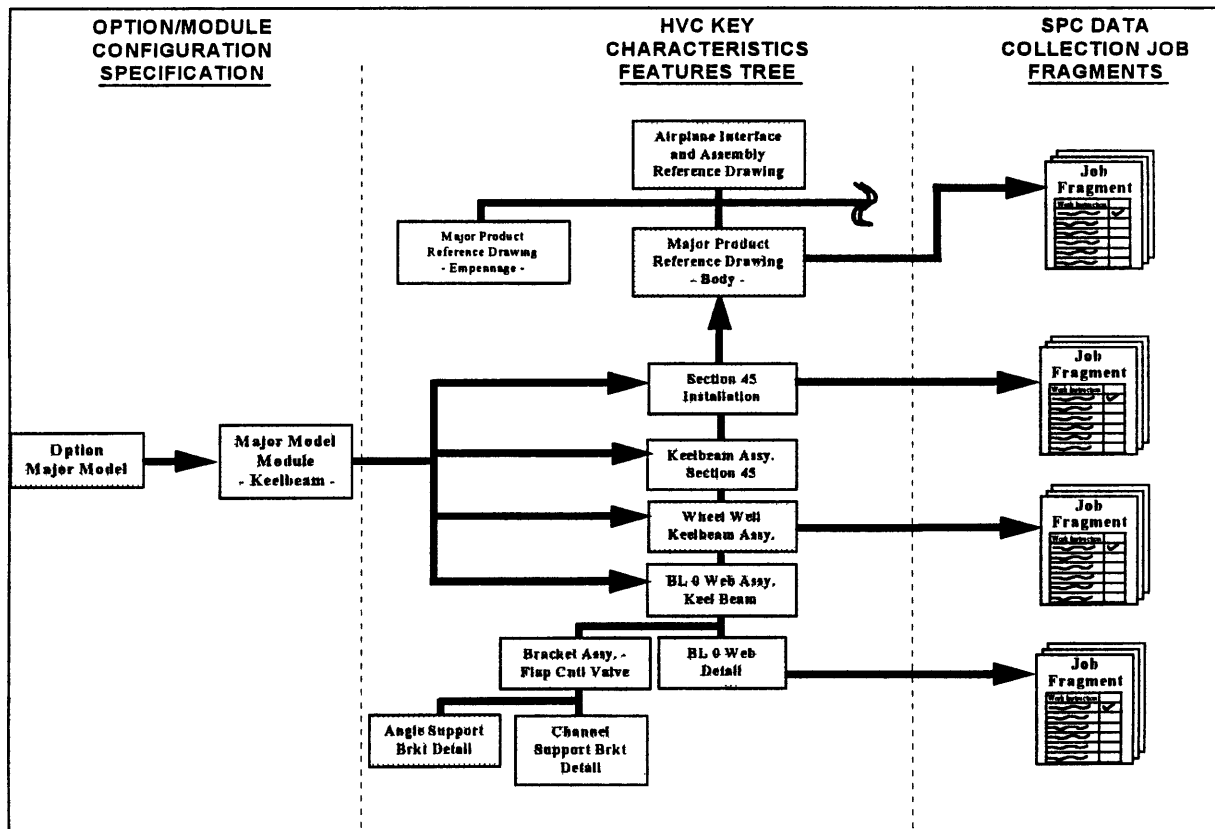
In summary, the Hardware Variability Control view establishes the relationship between top level aircraft features and features found on detail parts and assemblies. An example of a typical Hardware Variability Control features tree is shown in Figure 6.8.

Figure 6.8 - HVC View Flows Top Level Critical Dimension Into Detail Parts



The module based product architecture is highly compatible with the Hardware Variability Control initiative for three reasons. First, module based product structure is independent of the Hardware Variability Control features tree. This allows the creation of the necessary HVC reference drawings to allow a natural flow from top level airplane features to lower level features found on detail parts and assemblies. Second, the module based product architecture activates the SPC data collection using the relationship between the Functional Configuration Specification, Physical Design Configuration Specification and the Physical Production Configuration Specification. For example, when a customer selects an option, the corresponding module is activated in the Airplane Specific Configuration Table (ASCT). Activated modules contain part instances which are defined on drawings containing Key Characteristics. When part instances containing Key Characteristics are configured for a customer's aircraft, corresponding job fragments that implement SPC data collection are activated. This process is shown in Figure 6.9.

Figure 6.9 - Modules Activate Key Characteristics Data Collection Through The Drawings



In Figure 6.9, customer selection of the Major Model, activates the Keelbeam part instances . The part instance information contained in the module then activates drawings which contain the “Key Characteristics” notes. The part instance information in the module also activates the job fragments containing the SPC data collection instructions. This configures the work instructions which authorize the factory floor to collect the SPC data.

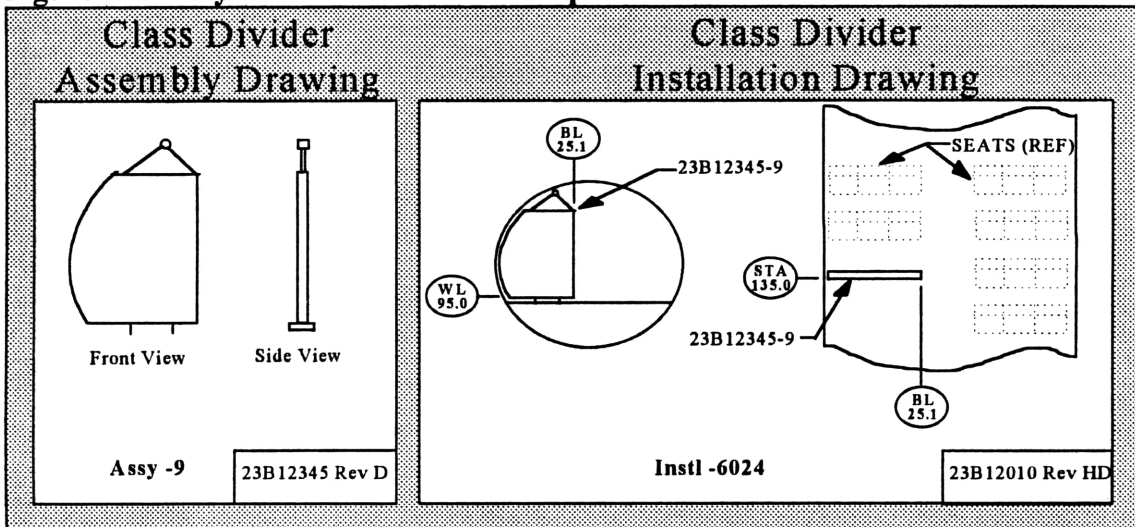
6.5 Modules Allow Creation of Parametric Installation Drawings To Maximize Design Re-use

Modules contain a significant amount of information which traditionally has been maintained on the drawing sheet. This provides an opportunity to configure parts on to the airplane parametrically using characteristics data in the module with no or minimal change to the engineering drawing. This is particularly useful for many of the items which are configured in to the interior of an aircraft. These items include seats, class dividers (partitions that separate first class from economy class), stow bins, closets and lavatories. Consider the stylized class divider shown in Figure 6.10. These dividers are designed in standard sizes and shapes. They attach to the seat tracks on the floor of the aircraft and a rail located near the roof of the airplane and can be located anywhere in the cabin. Although class dividers represent a standard design with well defined interfaces, issues such as class divider location and color require that engineering modify the drawing picture sheet and parts list whenever a new interior layout is developed. (New interior layouts are required for almost all customers.)

Today, the engineering drawings are continually modified to locate the class divider in the cabin and to apply customer selected colors and textures. The customer specifies the location of the class divider in the Layout Of Passenger Accommodations (LOPA) drawing. The location of the class dividers is noted by the design engineering community. Installation drawings are physically modified to show the new location (Figure 6.10), re-

tabulated with the customer's effectivity codes, and released to the manufacturing organization.

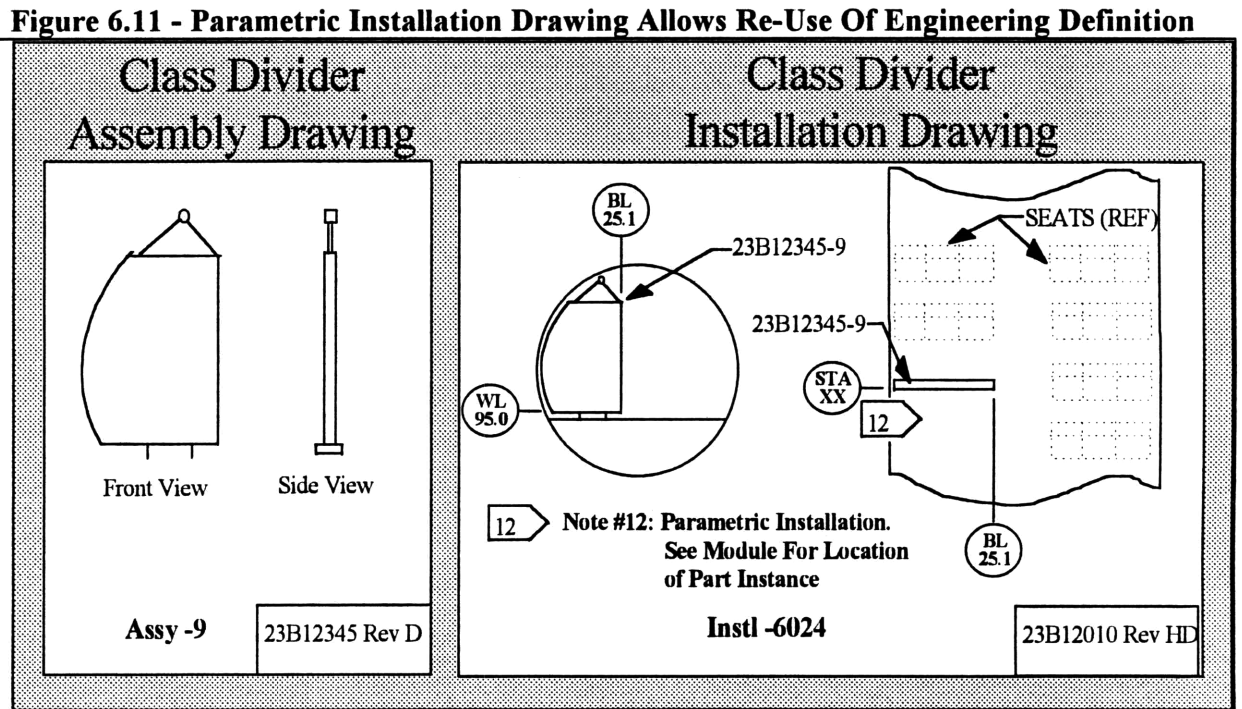
Figure 6.10 - Stylized Class Divider Example



In addition to modifying the engineering drawings for class divider location, other engineering drawings are modified to implement color. The class divider drawing contains a note in the parts list stating that the parts contained in the class divider assembly are colored. When a new aircraft is sold, the interior color is selected and defined in a memorandum. Colors are matched up with the appropriate decorative materials, 4 digit color codes are assigned, and an official coordination sheet is released to the design engineering organization. Design Engineering then modifies and releases the color code drawing which identifies color/decorative material codes against all of the class divider parts which receive color.

The module based product architecture has the potential to maximize design re-use by storing location and color related information as characteristics to the part. This eliminates data redundancy and moves toward an environment of sole authority engineering definition.

Parametric Installation Drawings To Eliminate Drawing Changes - The class divider installation drawing is re-released every time the divider is moved to a new position. To alleviate this problem, the installation drawing may be developed with a note code that identifies the modules for the position information of the part. This would allow the engineering drawing to be unaffected by moving the class divider from one location to another. This rearrangement of the engineering data is shown in Figure 6.11.



The installation drawing shown in Figure 6.11 has been “parameterized to allow re-use of the engineering definition. When a customer configures the class divider in different locations, only characteristics data surrounding the part instance need to be modified. By moving part location data off of the installation drawing and into the module, no manual modification of the engineering picture sheet is required. This allows these types of components to be configured electronically using a knowledge base without manual intervention. Although this is a very simple example, this philosophy can be used for several components that make up the interior of the aircraft. These include seat, stowage bins, closet and lavatory assemblies.

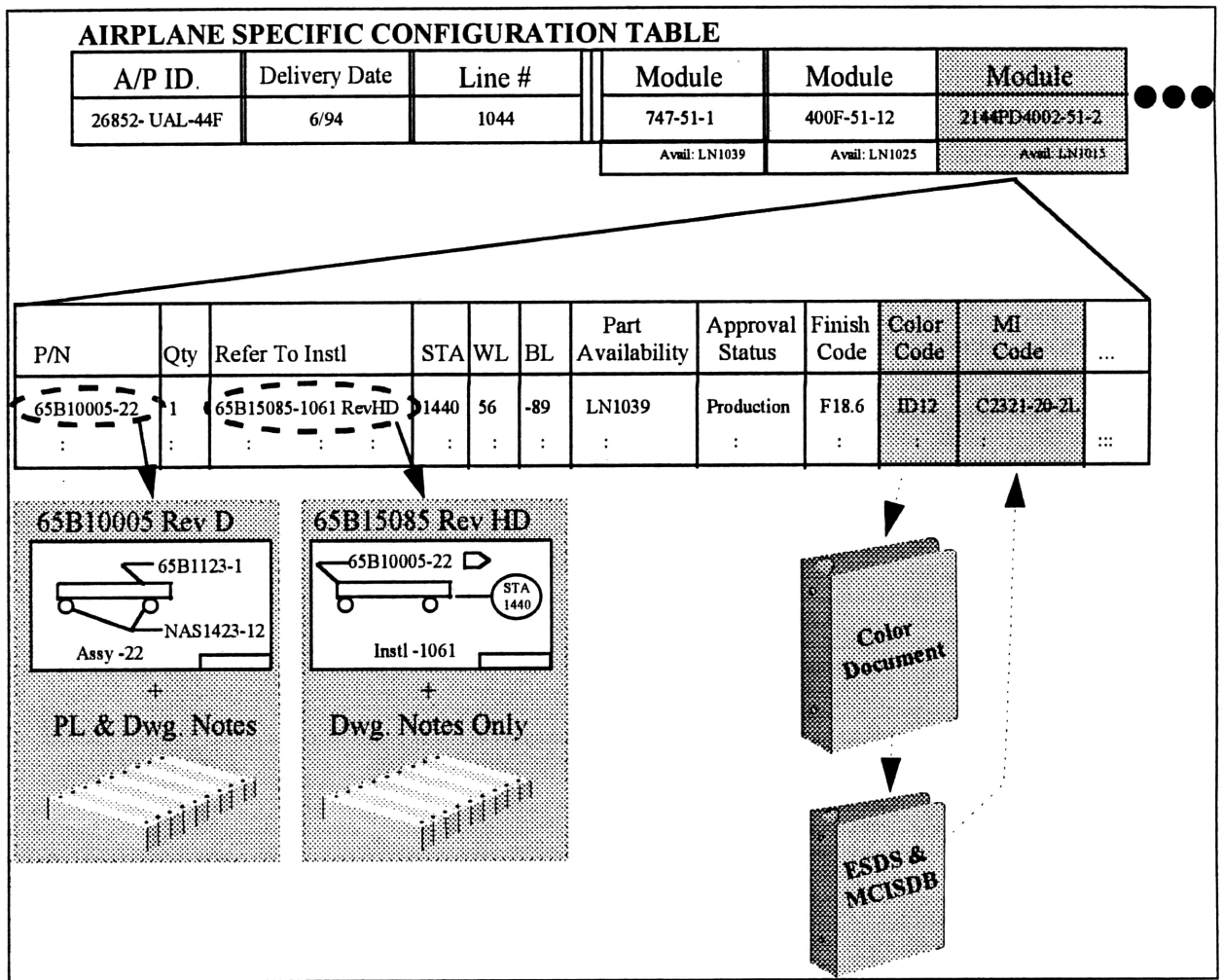
Elimination of Color Code Drawings Using Module Characteristics - Module

characteristics describe several aspects about the part that have been historically shown on the engineering drawing. Color definition is no exception. As described earlier, color definition is currently maintained in a color code drawing which assigns color/decorative material codes against the part. The color code drawing does not define geometric details, it simply assigns color codes. The module architecture allows elimination of the color code drawing by assigning color using part characteristics data contained inside the module. This allows the assignment of color from a library of color options contained in the color document thereby enabling design reuse.

Assignment of color is accomplished at multiple levels in the product structure. At the assembly level, color codes represent combinations of colors which are applied to the detail parts contained in the various assemblies. The detail parts also contain a color characteristic. These characteristics assign color and texture to the detail parts of interest. Consider a typical colored assembly contained in the module 2144PD4002-51-2 and shown in Figure 6.12.

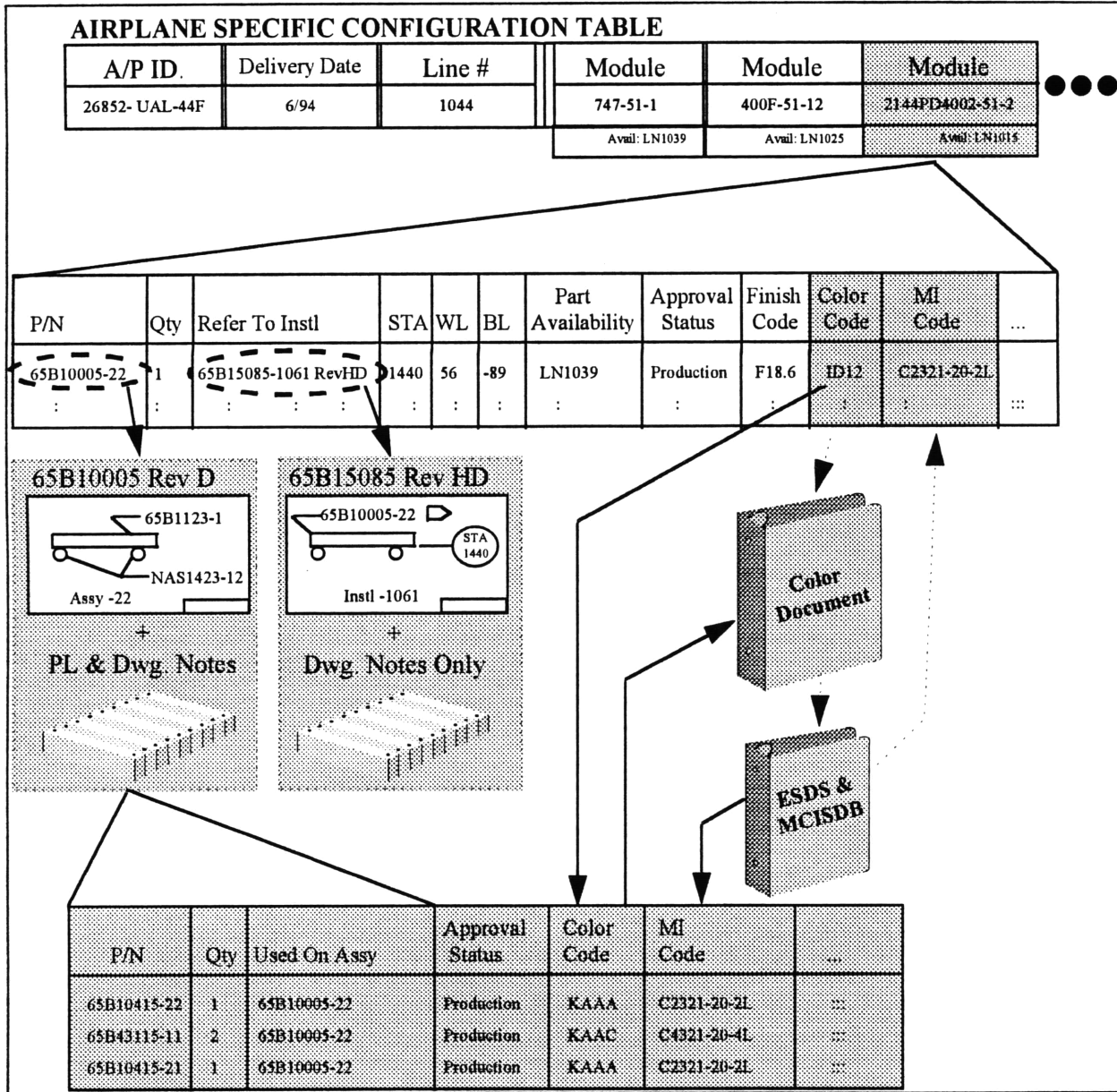
Color is assigned to the 65B1005-22 assembly using the four letter code "ID12". This code is transformed in to specific fabrication requirements using the color document and related BAC process specifications. Once color is defined, MI codes are retrieved using the ESDS system described in section 5.4. As described earlier, MI codes verify that the proposed material successfully meet certification requirements for use in the aircraft interior.

Figure 6.12 - Typical Module Contains Color Characteristics for Each Part Instance



Assemblies often contain detail parts which contain multiple colors and textures. The module based product architecture handles this situation by assigning characteristics directly to the detail parts which make up the assembly. These part characteristics allow each detail part to contain unique color and MI code. Color codes are applied to the detail parts through the color document. This type of product structure is shown in Figure 6.13.

Figure 6.13 - Detail Parts Derive Color From Assembly Codes



The color code "ID12" applied to the assembly has pre-defined color assignments for all of the colored details parts shown in the assembly. This allows a reusability of color combinations from previous designs. The module architecture provides a multiple level data structure allowing color characteristics to be carried directly with the definition of the part instances in a sole authority data base. This allows elimination of the color code

drawing thereby consolidating and simplifying the engineering definition. Maintaining color inside the module places the data in a relational data base. This allows electronic queries and simplifies the impact of change. For example, if a customer decides at the last minute that they did not like a particular shade of gray used on their vertical trim panels, a query can be generated to give all parts used on Airplane #26852-UAL-44F that contain the color code equal to gray. These changes may then be made electronically with out the manual manipulation of the engineering drawings.

6.6 New Product Architecture Leads The Way To True Feature Based Design Processes

Boeing leads the industry regarding advanced design techniques. Today, Boeing is designing aircraft using CATIA (Computer Aided Three Dimensional Interactive Application) design software. Engineers design in 3-D using computer generated solid geometry. These geometric elements fully represent features of parts and assemblies in the 3-D aircraft coordinate system. Parts are located in the aircraft coordinate system allowing electronic assemblies (electronic mock-up) to confirm design integration. Three dimensional design data enables the implementation of electronic assemblies while the parts are designed. This enables concurrent engineering processes and methods.

3-D Data Used In Manufacturing Improves Quality - Three Dimensional design is used to manufacture and inspect the parts using Computer Aided Manufacturing. Data can be downloaded from the CATIA workstation to fabrication machines which include 3 and 5 axis milling machines, tube bending devices, waterjet cutters, and tape lay-up machines etc. After the parts have been fabricated, Coordinate Measuring Machines (CMM's) are programmed directly from the three dimensional data to inspect part geometry.

By using the 3-D design data, manufacturing personnel no longer have to interpret the drawing picture sheet for machine programming instructions. Part geometry is explicitly defined everywhere in the 3-D environment. (It should be noted that CATIA V3.2, used on the 777 program, did not support exact solid modeling of all parts. Boundary

representation limitations as well as internal fillet radii modeling difficulties limit the fidelity of the solid models. However, recent developments in Computer Aided Design systems have demonstrated modeling new software that does support exact part definition of the solid models. These systems include CATIA V4.0, ProEngineer, Intergraph CADD5) By using a single source for 3-D data, manual recreation of the 3-D part definition to support Computer Aided Manufacturing CAM applications is not required. This eliminates a major source of error, reduces flow time and improves quality.

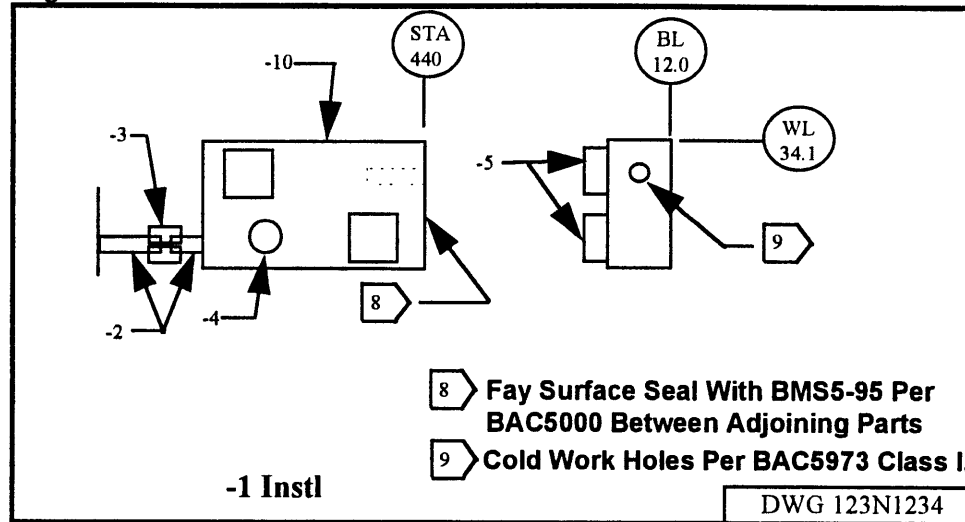
3-D Design and Fabrication Methods Have Not Eliminated The Need For Picture Sheets

- Although 3-D design methods and automated manufacturing have demonstrated the ability to design, fabricate and inspect aircraft components electronically, the engineering community continues to release thousands of drawing picture sheets. (The creation of the engineering picture sheet represents a level of effort that equals or exceeds the effort required to create the original 3-D definition.) The release of the engineering picture sheet in addition to the 3-D data creates multiple definitions of the part geometry. This results in ambiguity regarding which form of the engineering definition (2-D or 3-D) carries the authority for the part definition. With validated 3-D design, fabrication, and inspection capabilities, why do engineers continue to expend the effort to create and maintain the engineering picture sheet?

Engineering Picture Sheets Apply Non-Geometric Information Against Part Features -

Three dimensional CATIA data represent the physical geometry and tolerance requirements of a part. However, this data is only geometric data. The engineering definition contains non-geometric data which includes the raw material type, process specifications, finish specification, color specification to name only a few. There currently exists no tie between the geometric representation of the part and the non-geometric data which are both required to fabricate the part. An example of non-geometric data shown on a picture sheet is shown in Figure 6.14.

Figure 6.14 - Picture Sheet Contains Valuable Non-Geometric Data.

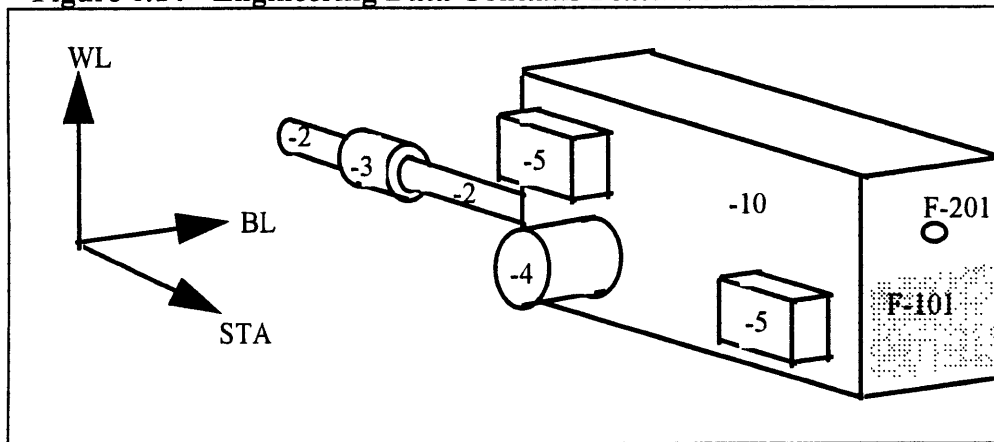


The 123N1234 installation drawing describes a stylized “widget” assembly. The engineering picture sheet shows each of the detail parts relative to the airplane coordinate system. This drawing also defines non-geometric information needed to properly install the parts. In particular, this drawing shows that the surface, located at station 1440, must be coated with a the BMS5-95 sealant prior to installation. In addition, the hole, located just below water line 34 and inboard of buttock line 12, must be cold worked per the process specification BAC 5973. The sealant and the cold working instructions are fundamental parts of the engineering definition which are not captured in a CATIA geometry system.

Modules Have Adequate Flexibility To Assign Non-Geocentric Data Against Part Features - The module based product architecture captures non-geometric data in the form of characteristics assigned to the part instance. Each part instance can collect non-geometric information that has been previously shown only on the drawing picture sheet. If you extend this part identification methodology to include part features, then you are able to assign non-geometric data to features located on a part. This allows the 3-D geometric data contained in the CATIA dataset and non-geometric data contained inside the module to completely contain all information that has been previously described on the drawing picture sheet. An example of feature instancing is shown in Figure 6.15.

Features are assigned unique identifiers. For example, the 123N1234-F-201 represents the hole located in the 132N1234-10 part. This feature identification methodology is similar to the part instance methodology described in section 4.0. Also, the cold working requirement “Cold Work Hole Per BAC5973 Class I.” is a characteristic assigned to the feature located in the part. Another feature shown on this part is the 123N1234-F-101 feature. The feature identification methodology uniquely identifies the sealant and locates it in the aircraft coordinate system. Sealant process requirements are characteristics of the feature. In this case the characteristic ”Fay Surface Seal With BMS5-95 Per BAC5000 Between Adjoining Parts” is assigned to the 123N1234-F-101 feature.

Figure 6.14 - Engineering Data Contains Feature Instances



The module based product architecture becomes the data base for non-geometric data which eliminates the need for the drawing picture sheet. These data are located in a relational data base which supports structured queries for ease and efficiency. The most important characteristic regarding the module based product architecture is that it deals effectively with both 3-D data as well as traditional drawing data. This allows the system to be implemented in a hybrid environment which contains 2-D drawing sheets as well as 3-D based product definitions. This consolidates a sole authority data base for non-geometric data allowing standardization of processes.

7.0 DATA CONVERSION

Implementation of this new data management system and configuration process requires extensive conversion of existing data. Effectivity must be removed from the existing drawings and parts lists. The function, physical design, and physical production configurations must align parts to the options they support. Modules must be created and fully characterized. Configuration rules must be developed and institutionalized. In this section, the data conversion activity will be described as it applies to conversion of the existing engineering drawings and bill of materials.

7.1 Conversion Of The Engineering Drawings Minimizes Re-Design Effort

A great temptation is to re-design the aircraft while conducting data conversion activities. This course of action, although feasible, is not recommended. Data conversion activities should first align the parts with the modules. Then cycle time analysis should be performed similar to the analysis presented in section 5.4 to identify designs that have high leverage for reduction of cycle time. Without understanding which component designs are critical path for a particular option, re-design activities are unlikely to adequately focus on the root cause of the cycle time problem. Therefore, initial data conversion efforts ought not to include re-design activities. Re-design efforts should be implemented only as needed and then only after the module based product architecture has been implemented. This allows re-design activities to only be deployed on the parts that are on the “critical path” thereby leveraging re-design investment to drastically reduce cycle time and aircraft total cost.

The amount of effort required to convert the existing engineering data to the module based product architecture depends on the relationship between the parts and the options they support, as well as the complexity of the effectivity tabulation. The types of drawings that must be converted include installation drawings, assembly drawings, limited part

collectors, and detail part drawings. The following analysis will describe the conversion activity for each of the types of drawings previously described.

Installation Drawings - Standard installation drawings define the configuration of the hardware in the aircraft coordinate system. Since the location of the parts and assemblies are known, they can be mapped directly in to module. Conversion scenarios have been developed around representative installation drawings in terms of part to option relationships and effectivity tabulation. These scenarios include:

Scenario #1: Single installation drawing with all parts supporting a single option.

Scenario #2: Single installation drawing containing parts which support multiple options.

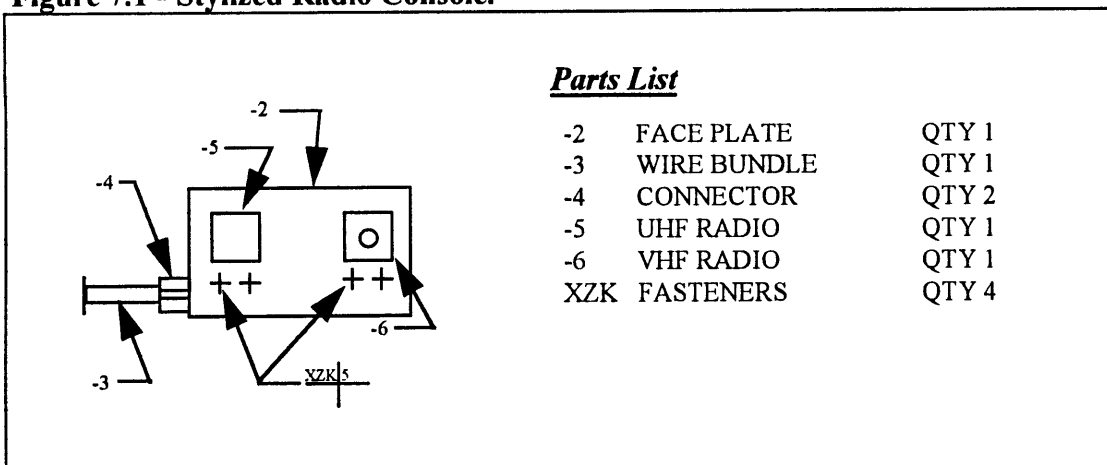
Scenario #3: Multiple installation drawings that together support a single option.

Scenario #4: Single installation with complex effectivity defining multiple configurations.

Scenario #5: Single installation customized for a combination of options.

A stylized radio console will be used to illuminate the salient features of the conversion activity for all of the scenarios described above. This basic version of the radio console is shown in Figure 7.1.

Figure 7.1 - Stylized Radio Console.



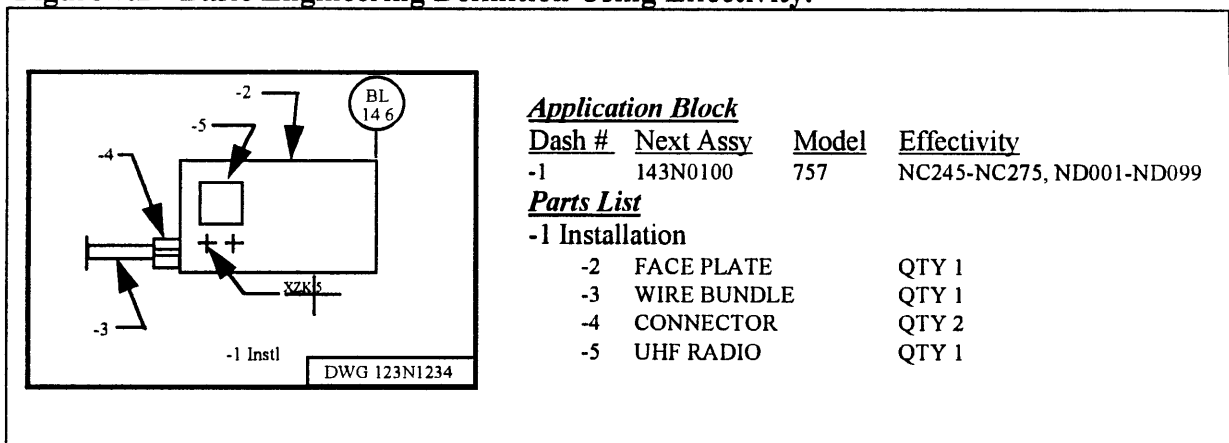
The basic radio is composed of six components which include a face plate detail part, wire bundle assembly, connector assembly, UHF and VHF radio's and fasteners. For simplicity, antenna and antenna related hardware were not included in this example. These components can be configured in a variety ways depending on the options selected in the functional configuration specification. Consider the first scenario.

Scenario #1: Single installation drawing with all parts supporting a single option.

This scenario describes the installation of a single UHF radio on the aircraft. In this scenario, assume that the UHF radio is only installed on the aircraft when the customer explicitly requests the UHF radio option. Conversely, if the customer does not select the UHF radio option, the UHF radio, face plate, wire bundle, connectors, and fasteners are not configured on to the aircraft.

Using an effectivity based system, the engineering definition for this scenario would appear as is shown in Figure 7.2. This definition includes the installation picture sheet, application block and parts list.

Figure 7.2 - Basic Engineering Definition Using Effectivity.

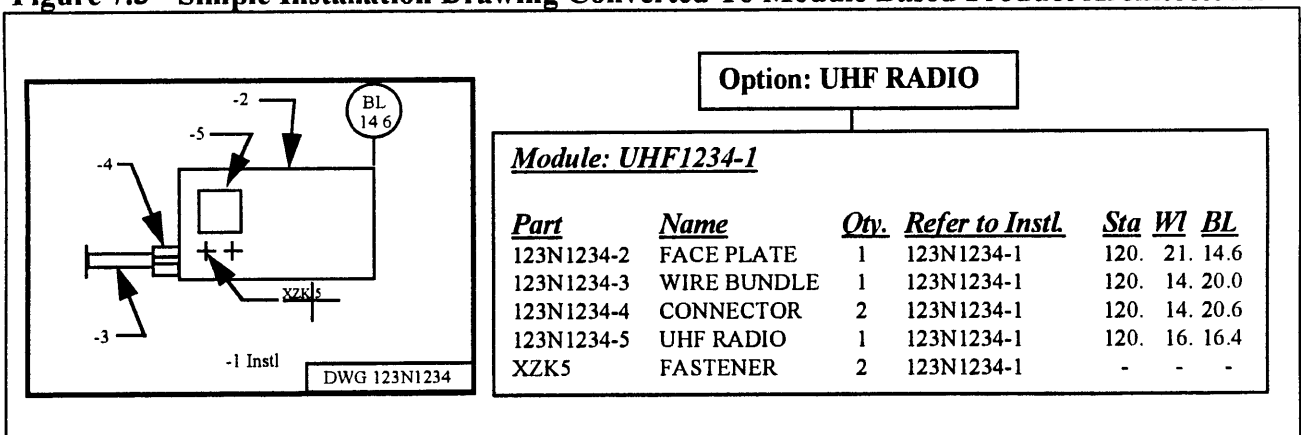


The picture sheet describes the part geometry in the aircraft coordinate system. It identifies each part and fastener. Parts are described by their dash number, Fasteners are defined using a standard "fastener code". In this case, the fastener type XZK 5 represents

a basic rivet made from 2017-T4 with a diameter equal to 5/32 inch. The “Application Block” in the parts list shows which aircraft effectivities the installation is active. The parts lists shown all of the parts that belong to the 123N1234-1 installation. It should be noted that today’s parts lists typically do contain fastener requirements.

In order to convert this data a module must be created. The module relates the UHF radio option to all of the part instances required to implement the option on to the aircraft. The drawing and parts lists (shown in Figure 7.2) was converted to the module based product architecture and is shown in Figure 7.3. Although the parts lists have been significantly changed, no changes to the picture sheet were required. Fasteners are shown explicitly in the module. This allows the aircraft Bill of Materials to contain 100% of the parts on an aircraft. Incorporating fasteners into the Bill of Material has several benefits. These include (1) improved accuracy of the “As Planned“ Bill Of Materials, (2) reduced inventory levels of all Shop Distribution Standards such as fasteners, nut plates, etc. (3) accurate tracking of the “As Built” aircraft by explicitly recording changes to the “As Planned” configuration as the aircraft evolves to the “As Built” configuration (4) elimination of part substitution documents on the factory floor.

Figure 7.3 - Simple Installation Drawing Converted To Module Based Product Architecture.

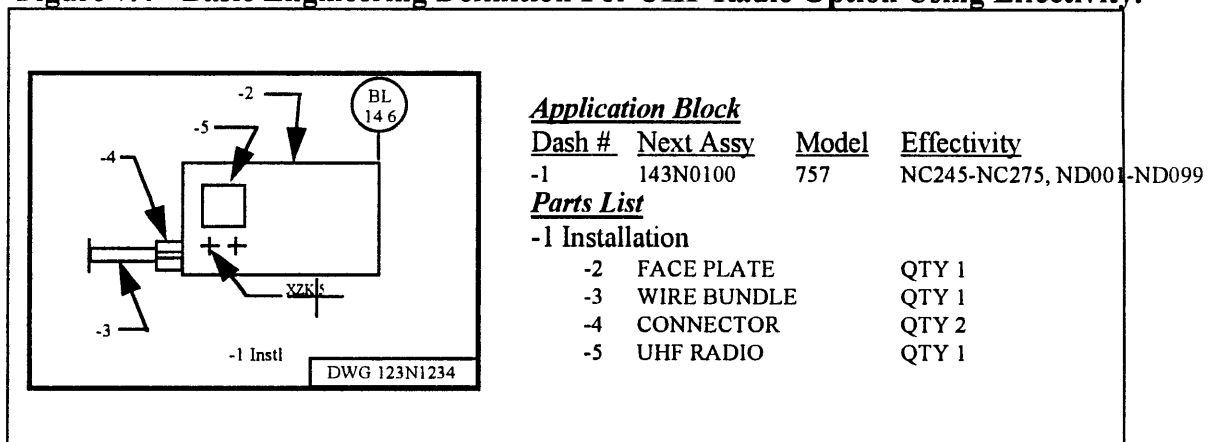


Scenario #2: Single installation drawing containing parts which support multiple options.

This scenario describes a UHF radio installation similar to scenario #1. However, this scenario assumes that the face plate is used on every aircraft. If the UHF radio is ordered, then the face plate supports the radio. If the UHF radio is not ordered, then the face plate is used to complete the instrument panel. This allows the face plate to be used on every aircraft. If we assume that the aircraft is the 757, then the face plate is “basic and stable” on every 757 aircraft produced by The Boeing Company. Further assume that the UHF radio, wire bundle, connector, and fasteners configure onto the aircraft only when the customer selects the UHF radio option.

Using an effectivity based system, the engineering design is customized to support the aircraft with the radio and without the radio. One installation drawing implements the face plate with out the UHF radio, and a second installation drawing implements the face plate without the UHF. The installation drawing which installs the UHF radio is shown in Figure 7.4.

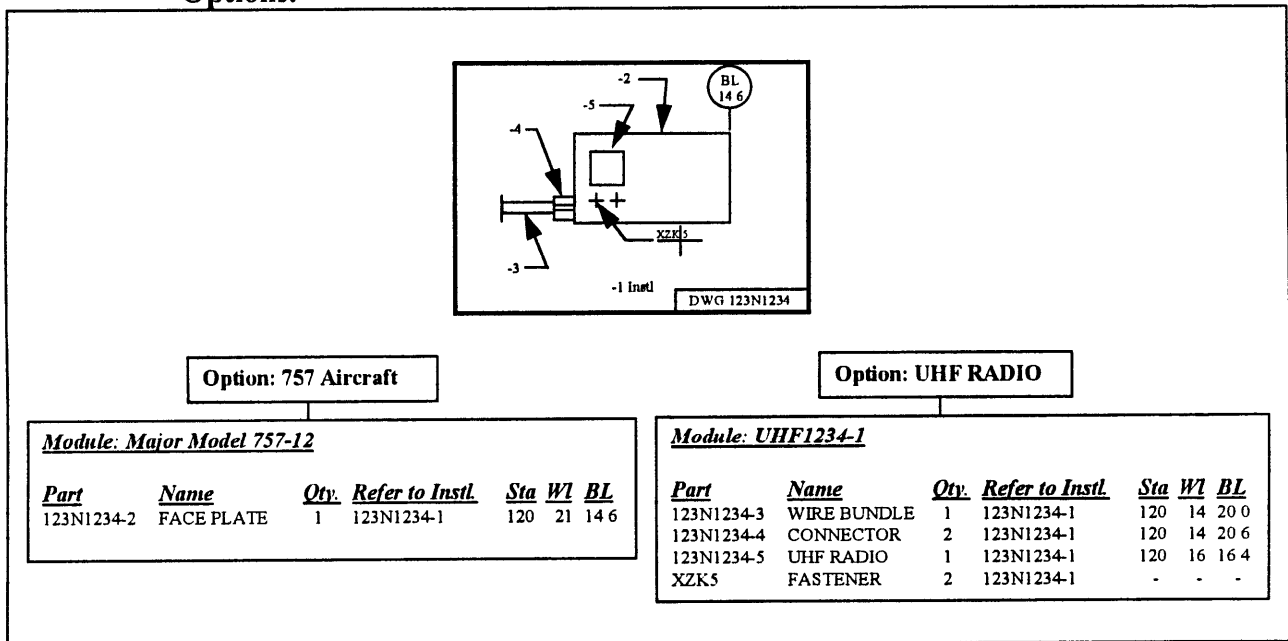
Figure 7.4 - Basic Engineering Definition For UHF Radio Option Using Effectivity.



Again, this engineering definition contains a picture sheet, application block, and parts list. Conversion of this data to the module based product architecture requires that the parts list information be converted into two modules: the 757 Major Model Module and the UHF Radio Module. The “Face Plate” belongs to the Major Model Module since it is

“basic and stable” on every aircraft. The UHF radio, wire bundle, connectors and fasteners belong in the UHF1234-1 module which is activated in the Airplane Specific Configuration Table (ASCT) only when the customer selects the UHF radio option. Therefore, when a customer selects a 757, the face plate is configured on to the aircraft. In addition, if a customer selects the UHF radio option, the UHF radio, wire bundle, and fasteners are configured on to the airplane. The drawing and parts lists shown in Figure 7.4 were converted and is shown in Figure 7.5. This figure graphically shows the 757 aircraft option and the UHF Radio option. Also shown are the relationships between the option and the module containing the part instances. When the option is selected, the module and all of the part instances contained in the module are configured onto the aircraft. Although the parts lists have been significantly changed, no changes to the picture sheet were required.

Figure 7.5 - Conversion Of A Single Installation Containing Parts Which Support Multiple Options.

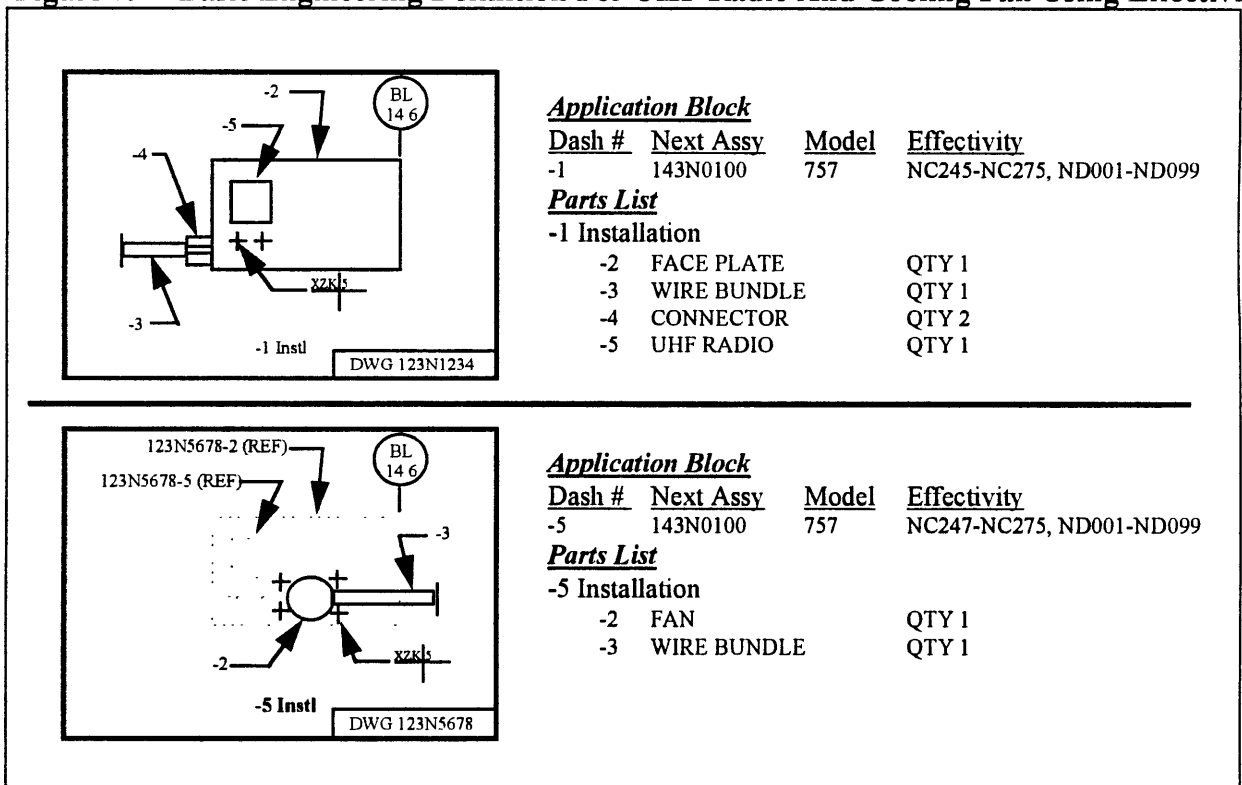


Scenario #3: Multiple installation drawings that together support a single option.

This scenario describes a radio installation which describes a UHF radio installation. However, in this situation, assume that if a UHF radio is selected, an additional cooling fan must be installed and that the cooling fan is described on a separate installation drawing. Again, assume that the face plate has provisions for both the radio and the fan. (This allows the face plate to be “basic and stable” to the major model.) Also assume that the UHF radio, **cooling fan**, wire bundle, connector, fasteners configure onto the aircraft only when the customer selects the UHF radio option.

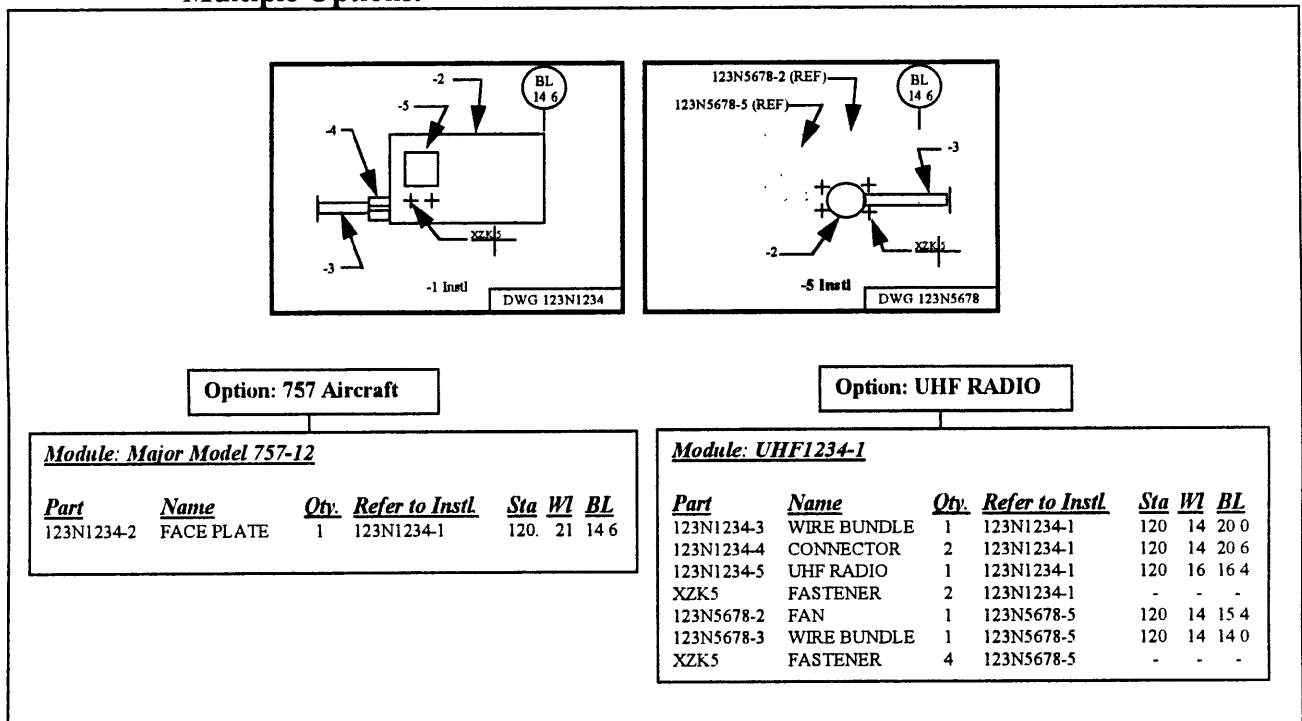
Figure 7.6 depicts the engineering definition as it appears in today’s effectivity based system. Again, the engineering definition includes the installation picture sheet, application block, and parts list for each of the drawings.

Figure 7.6 - Basic Engineering Definition For UHF Radio And Cooling Fan Using Effectivity.



Conversion of the engineering data for this particular scenario requires that the parts list information be converted into two modules: the 757 Major Model Module and the UHF Radio Module. The “Face Plate” belongs to the 757 Major Model Module. The UHF radio, fan, wire bundle, connectors and fasteners belong in the UHF1234-1 module. The drawing and parts lists shown in Figure 7.6 was converted and is shown in Figure 7.7. This figure graphically shows the 757 aircraft option, the UHF Radio option and supporting modules containing the part instances. When the option is selected, the module and all of the part instances contained in the module are configured onto the aircraft. Although the parts lists have been significantly changed, no changes to the picture sheet were required. It should be noted that the “refer to instl” characteristic in the module allows parts from multiple installation drawings to be contained in a single module.

Figure 7.7 - Conversion Of Multiple Installation Drawings Containing Parts Which Support Multiple Options.

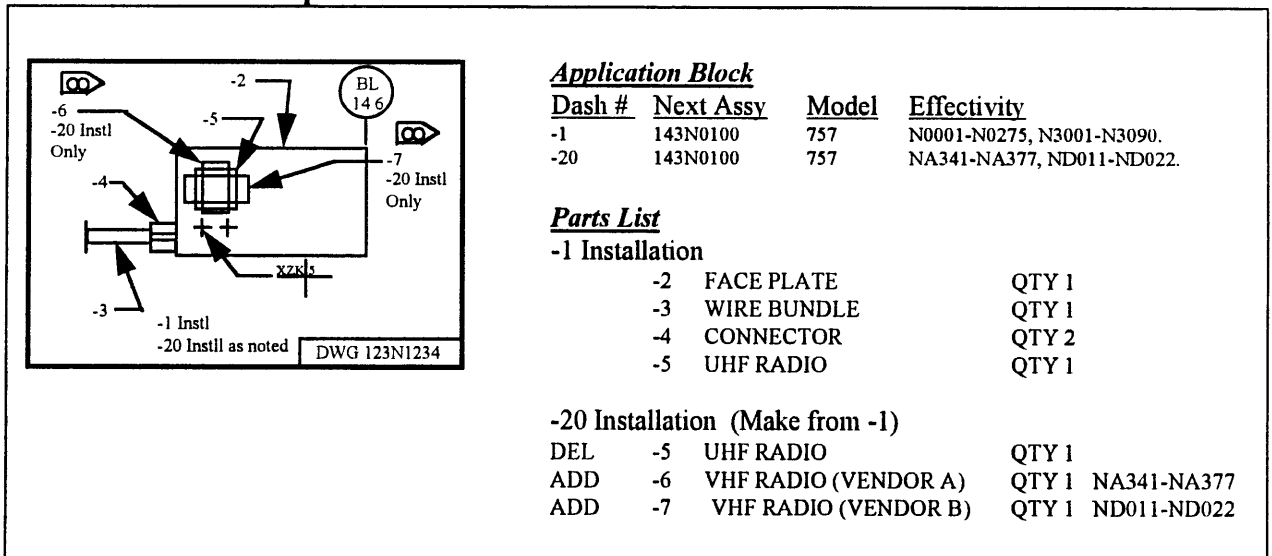


Scenario #4: Single installation with complex effectivity defining multiple configurations.

This scenario describes a single radio installation drawing which defines multiple hardware configurations on the same picture sheet. This scenario describes the installation of UHF and VHF radios. Both of these installations are described by the 123N1234 drawing. The picture sheet has been internally limited using effectivity to discriminate the UHF radio configuration from the VHF radio configuration. In this scenario, assume that all 757 aircraft must be configured with a radio. (This makes the face plate, wire bundle, connector basic and stable for all 757 aircraft.) Assume that the UHF radio is installed on the aircraft only when the customer selects the UHF radio option. The VHF radios are vendor specific. Assume that the VHF radio for a specific vendor is installed only when the customer selects the appropriate VHF radio option.

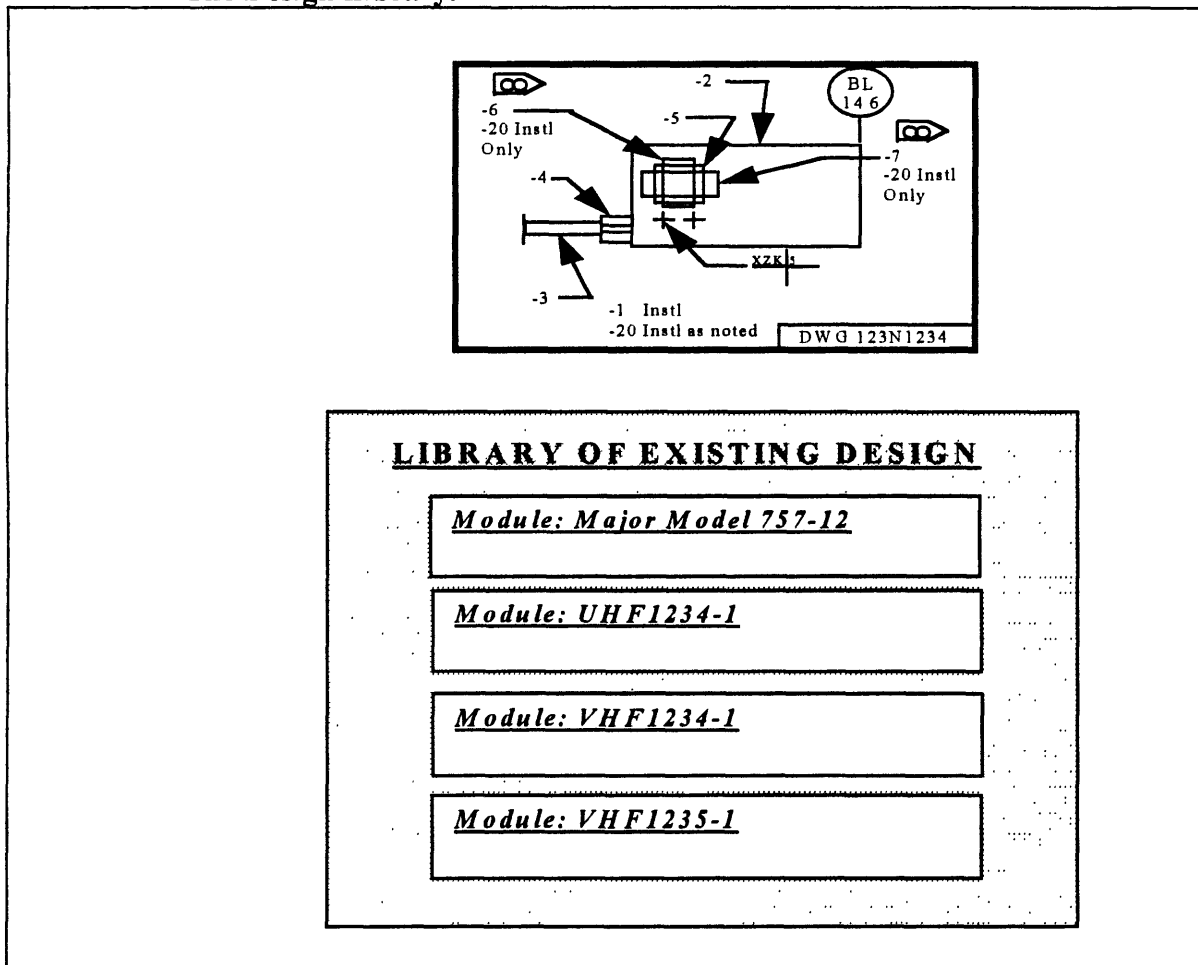
Figure 7.8 depicts the engineering definition as it would appear today. Note that the 123N1234-20 installation specifies the configuration using a flag note on the picture sheet which internally limits the configuration of the parts list at several levels. In this case, effectivity is specified for the -20 installation (NA341-NA377, ND011-ND022), the -6 VHF radio (NA341-NA377) as well as the -7 VHF Radio (ND011-ND022).

Figure 7.8 - Basic Engineering Definition For Internally Limited Drawing Has Effectivity At Multiple Levels.



Conversion of this engineering data for this particular scenario requires that the parts list information be converted into four modules: the 757 Major Model Module and the UHF Radio Module, VHF Radio (Vendor A) Module, and the VHF Radio (Vendor B) Module. This scenario describes multiple configurations which cannot all be incorporated in to the same aircraft at the same time. Only the modules which support those options specifically requested by the customers are brought in to the configuration for a single aircraft. This scenario, unlike the previous scenarios described earlier, shows that the converted modules reside in a reusable design library containing all modules. This design library with the four modules resulting from the conversion activity is shown in shown in Figure 7.9.

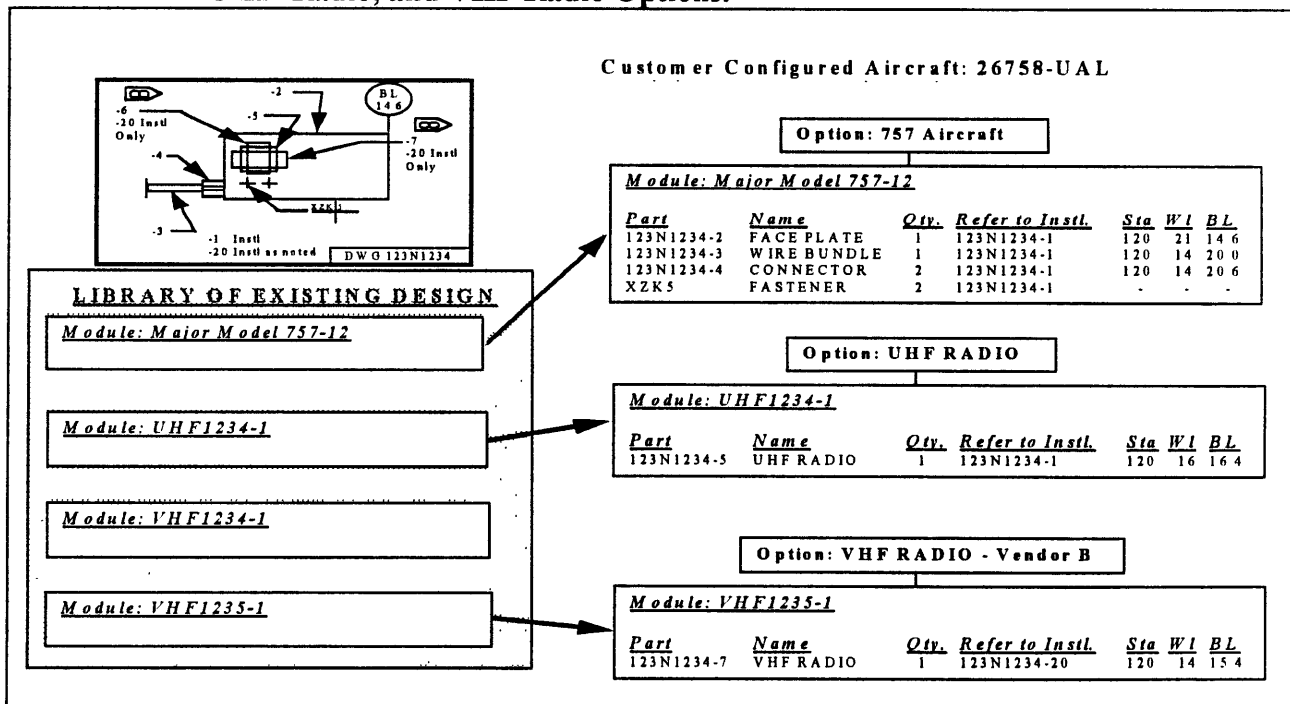
Figure 7.9 - Conversion Of Single Installation Drawing Adds Four Modules To The Design Library.



The face plate, wire bundle, connector and common fasteners belong to the “Major Model Module”. The UHF radio belongs to the “UHF 1234-1 Module”. The VHF radio manufactured by Vendor A belongs to the “VHF 1234-1 Module”. The VHF radio manufactured by Vendor B belongs to the “VHF 1235-1 Module”. Conversion of this data populates the modules with the part instances which support the customer selected options. Customer selected options activate the appropriate modules which are shown in Figure 7.9. Once activated, the module configures the aircraft with the correct part instances.

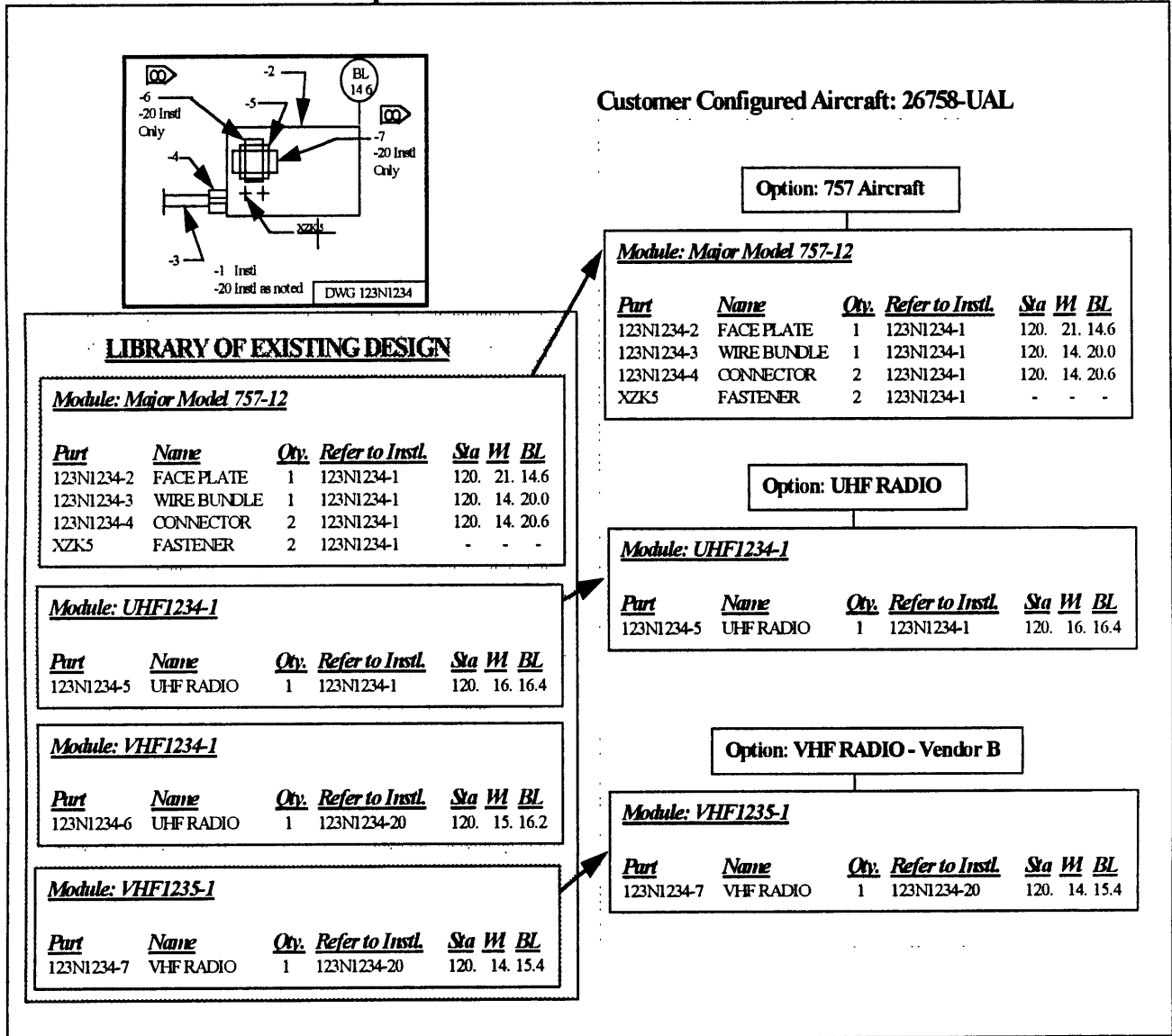
For example, consider the case where a customer requests a 757, a UHF radio, and a VHF radio manufactured by vendor A. These options configure the appropriate modules onto the customer’s aircraft as is shown in Figure 7.10. Note that drawing and parts list data have been significantly altered. However, no changes to the picture sheet were required.

Figure 7.10 - Customer Airplane Configured From Design Library To Include 757, UHF Radio, and VHF Radio Options.



The design library contains not only the module identifiers, but all of the part, plans, and tooling data required to implement that part an aircraft. Figure 7.10 was expanded to show the engineering content in the design Library and is shown in Figure 7.11.

Figure 7.11 - Design Library Contains All Relevant Information to Completely Configure a Customer's Airplane.



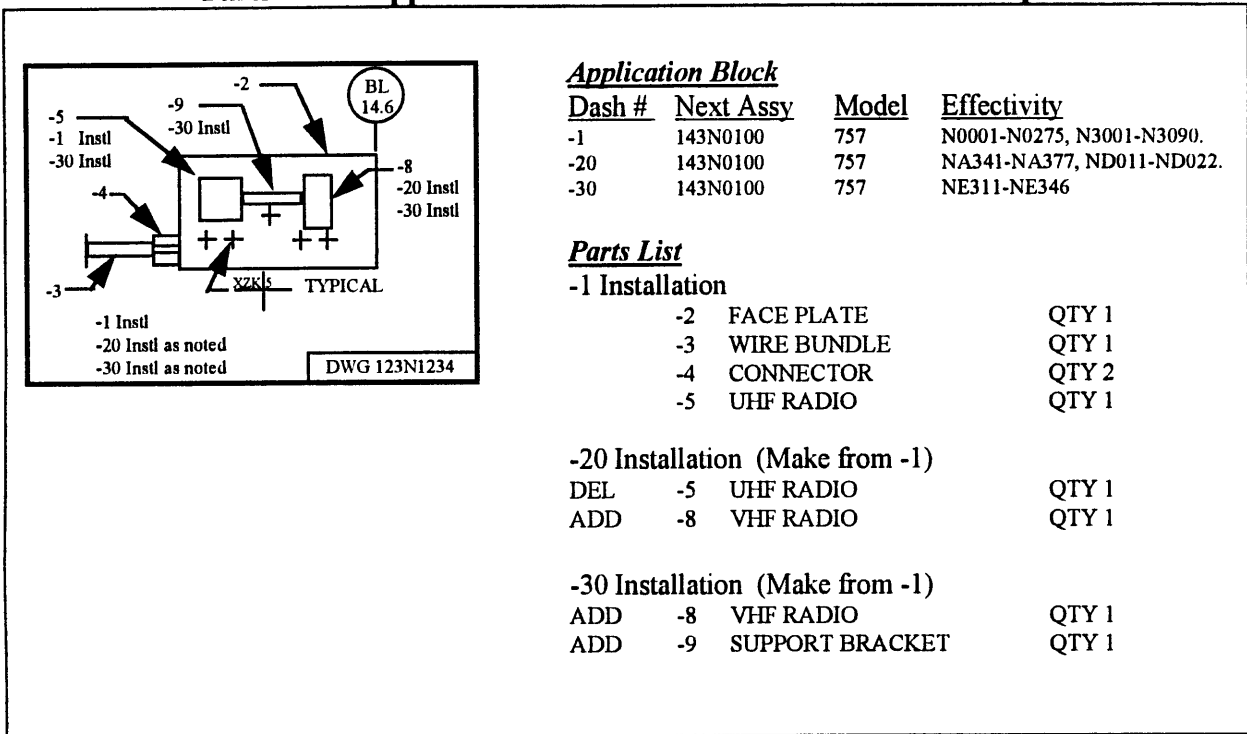
Scenario #5: Single installation drawing customized for a combination of options.

This scenario describes an installation drawing which installs the UHF and VHF radios either separately or in combination. This scenario assumes that when both radios are installed, strength limitations of the face plate require that an additional support bracket be installed. Assume that all aircraft require at least one radio. All of the installations are described by the 123N1234 drawing. The picture sheet has been internally limited using effectivity. As before, assume that the **UHF** radio configures onto the aircraft only when the customer selects the UHF radio option. Assume that the **VHF** radios configure onto the aircraft only when the customer selects the VHF radio option.

Figure 7.12 depicts the engineering definition as it would appear using today's effectivity based system. The 123N1234-1 installation specifies the installation of the UHF radio by itself. The 123N1234-20 installation specifies the installation of the VHF radio by itself. The 123N1234-30 installation specifies the installation of both the UHF and VHF radios. It should be noted that when both radios are installed the 123N1234-8 support bracket is required.

Again, effectivity is used to specify the configuration of the aircraft. In this scenario, all of the effectivity is contained in the application block. The 123N1234-1 installation is effective for aircraft N0001 through N0275 and N3001 through N3090. The 123N1234-20 installation is effective for aircraft NA341 through NA377 and ND011 through ND022. The 123N1234-30 installation is effective for aircraft NE311 through NE346.

Figure 7.12 - Basic Engineering Definition For Internally Limited Drawing With Parts That Support A Combination Of Customer Selected Options.



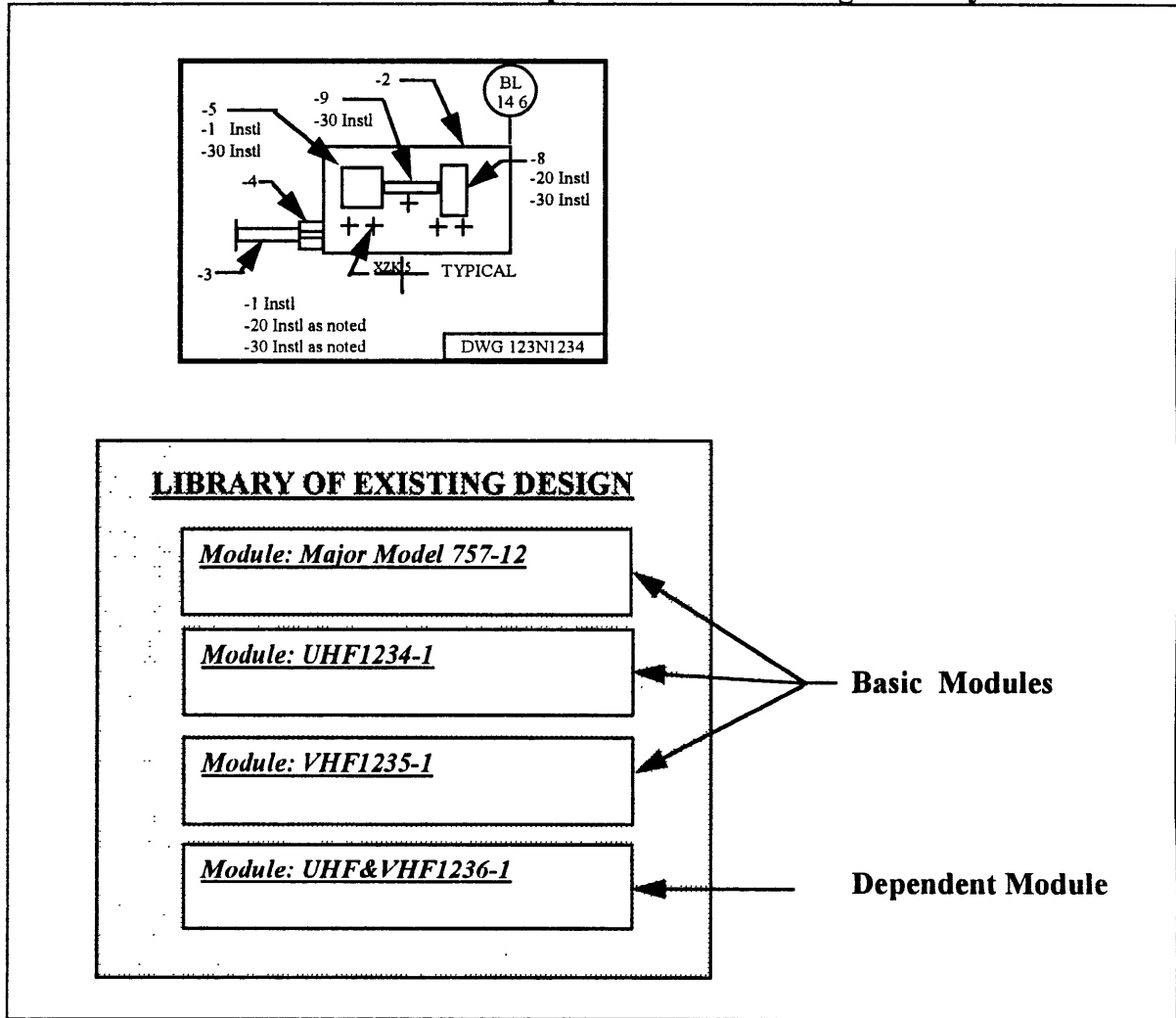
Conversion of this engineering data for this particular scenario requires that the parts list information be converted into basic and dependent modules. The basic modules includes the 757 Model Module, the “UHF” Module (UHF1234-1), and the “VHF” Module (VHF1235-1). The dependent module is the “UHF and VHF” Module (UHF&VFH1236-1).²²

This scenario describes multiple configurations which cannot all be incorporated in to the same aircraft at the same time. Only the modules which support specific options requested by the customer are brought in to the configuration for a single aircraft. All modules reside in a re-useable design library. The design library with the four modules described previously are shown in Figure 7.13. Although, the modules developed in this scenario are similar to those developed in scenario #4, the part instances contained in each

²² Dependent modules require computerized configuration logic. The configuration logic is described in section 7.3.

module and rules used to configure these modules onto the aircraft are considerably different.

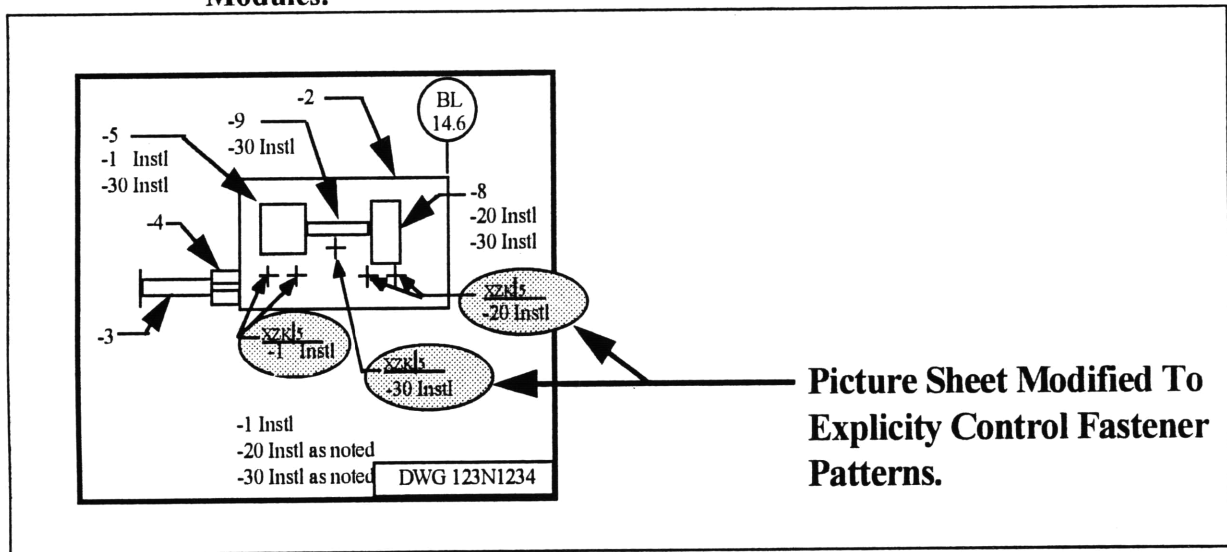
Figure 7.13 - Conversion Activity Creates a Basic Module and Three Dependent Modules Which Are Incorporated Into The Design Library.



The face plate, wire bundle, and connectors belong to the “Major Model Module”. The UHF radio and two fasteners that are needed to install the radio belong to the “UHF1234-1 Module”. The VHF radio and the two fasteners that are needed to install the radio belong to the “VHF1235-1 Module”. The support bracket and fastener required to install the bracket belongs to the “UHF&VHF1236-1 module”.

This scenario requires that the picture sheet be altered. The existing picture sheet does not explicitly define the use of fasteners. Since fasteners are not replicated in today's parts list, fasteners requirements are interpreted from the picture sheet. This is especially complex when substitutions are made on the factory floor. (These substitutions are legitimized via an official part substitutions document.) In converting the engineering into the modules, the fasteners patterns are explicitly controlled. This required that the fasteners be unambiguously defined in the module. This can be done in one of two ways. The first method is to record the location of the fastener in the aircraft coordinate system explicitly in the module. The second is to declare the fastener pattern as part of an installation drawing number. The later approach has been used in this scenario. This requires that the picture sheet be modified as is shown in Figure 7.14.

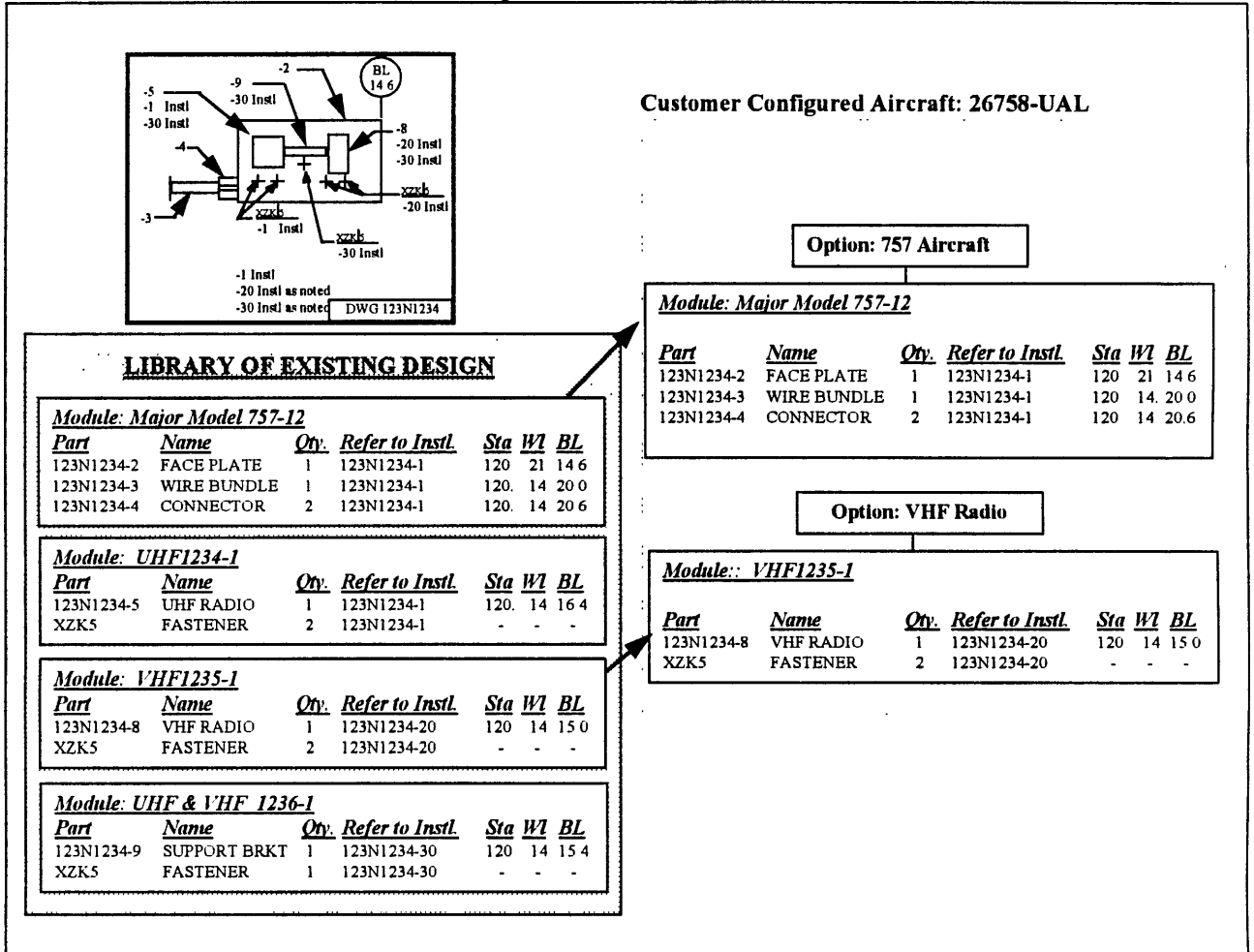
Figure 7.14 - Conversion Of Installation Drawing With Complex Effectivity Into Modules.



Conversion of part list data populates the modules with the fully characterizes part instances which support selected options.

Consider an example where a customer requests a 757, and a VHF radio. These options configure the appropriate modules onto the customers aircraft as is shown in Figure 7.15.

Figure 7.15 - Customer Airplane Configured From Design Library To Include 757, and VHF Radio Options.



The dependent module (UHF&VHF1236-1) configures onto an aircraft only when the VHF and UHF options are selected together. If a customer were to request the 757 option with the UHF and VHF radio options, the design library will activate modules 757-12, UHF1234-1, VHF1235-1, and UHF&VHF1236-1 in the ASCT. These modules will then configure the bill of materials, plans and tools required to deliver the customer's airplane.

Scenario #5 creates a situation where parts configure on to a customer's aircraft only when the UHF and VHF options are selected **together**. Other situations will arise where parts configure onto an aircraft only when "Option A" is selected and "options B" is **not** selected.

Cases where parts configure on an aircraft only when other options are not selected also create dependent modules. In these cases, the resulting dependent module is configured onto the aircraft only when the Boolean expression (e.g. “Option A and Not Options B”) representing the option condition is completely satisfied.

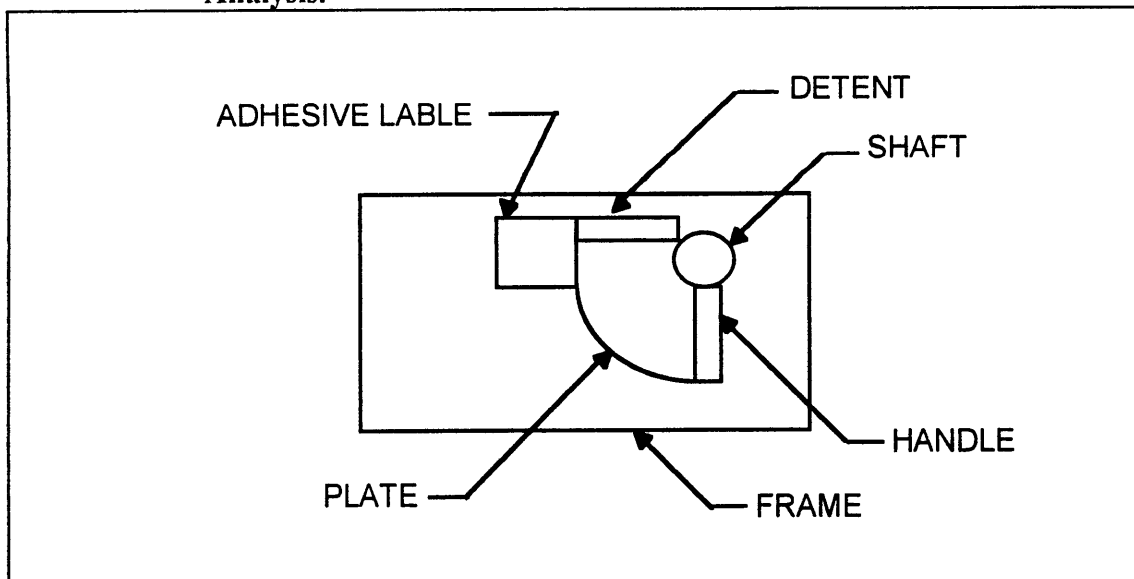
Assembly Drawings - Assembly drawings differ from installation drawing in that they do not explicitly locate the parts in the aircraft coordinate system. These drawings define the “part instance” shown in the module. Assembly drawings are part number controlled end items. Conversion of assembly drawings to this new product architecture must eliminate internal effectivity limitations, and fully characterize the part list. Conversion scenarios have been developed around representative assembly drawings. These scenarios include:

Scenario #6: Basic assembly drawing with short form tabulation.

Scenario #7: Internally limited assembly drawings “-5000 Limited Parts Collector”.

Scenario #6 and Scenario #7 will be developed around a stylized door latch mechanism. The basic mechanism is shown in Figure 7.16.

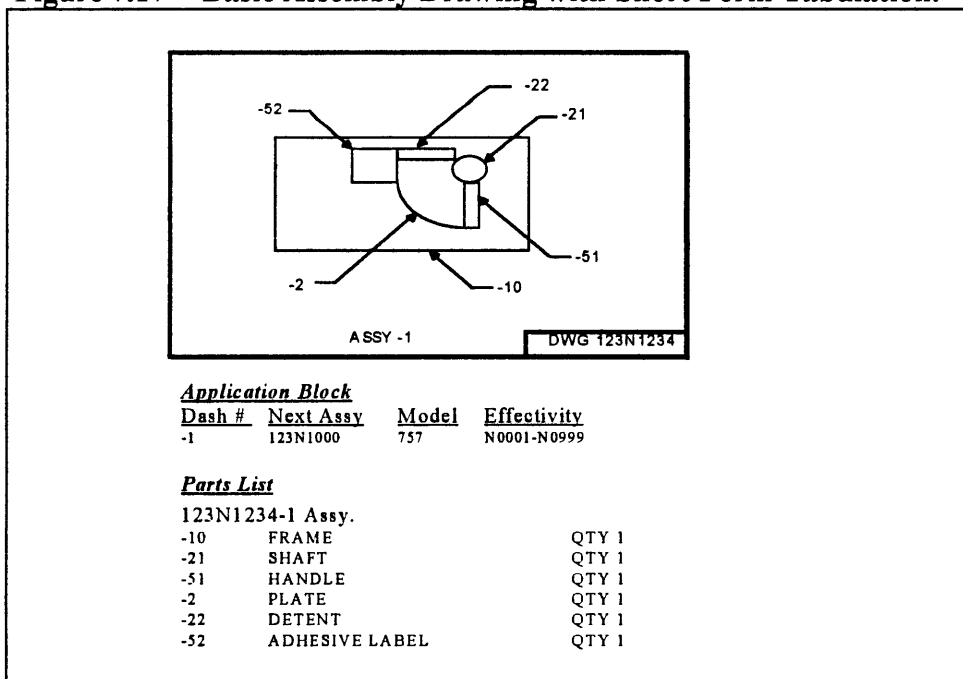
Figure 7.16 - Stylized Door Latch Assembly Used In Assembly Drawing Scenario Analysis.



Scenario #6: Basic assembly drawing with short form tabulation.

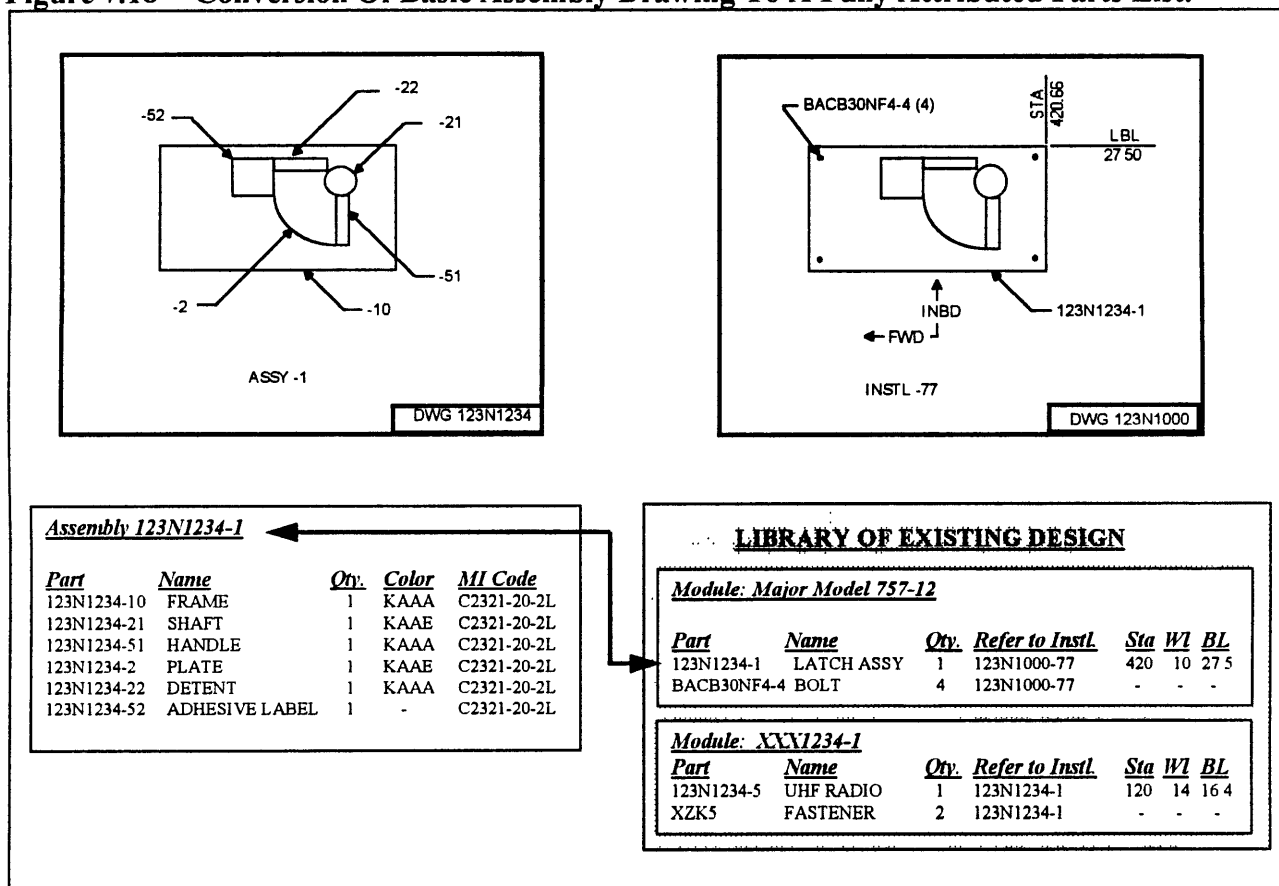
Conversion of the basic assembly drawing with short form tabulation is relatively straight forward. Short form tabulation means that the effectivity for the assembly is inherited from the next higher drawing in the drawing tree. Consider an assembly drawing which defines a door latch assembly. as it would appear in today's system as is shown in Figure 7.17. This latch consists of a frame, shaft, handle, plate, handle detent and adhesive label. In this scenario, assume that the assembly has been pure part number controlled. Since this particular assembly uses "short form tabulation", the next higher assembly (123N1000) determines the specific effectivity through the application block. It should be noted that the components which make up the assembly are not positioned in the aircraft coordinate system and cannot be made a direct member of a module. Since the components are not located in the aircraft coordinate system, they do not have a part instance to record in the module. This requires that the assembly and its components be part number controlled. Since the assembly is an inspectable end item, the assembly parts lists and the picture sheet must always be synchronized.

Figure 7.17 - Basic Assembly Drawing with Short Form Tabulation.



Conversion of the basic assembly is relatively simple. The existing drawing picture sheet has no internal effectivity limitations and requires no modification. Conversion of the parts list data requires that the parts be characterized with the appropriate engineering data. Typical engineering characteristics are described in section 5.0. Figure 7.18 shows the converted assembly drawing as well as the relationship between the assembly, module, and installation drawing. The option (757) is related to the Module (757 Major Model Module). The module contains the assembly instance (123N1234-1 located as is shown on the installation drawing 123N1000-77 picture sheet). The assembly instance identifies the part number controlled assembly drawing (1123N1234-1).

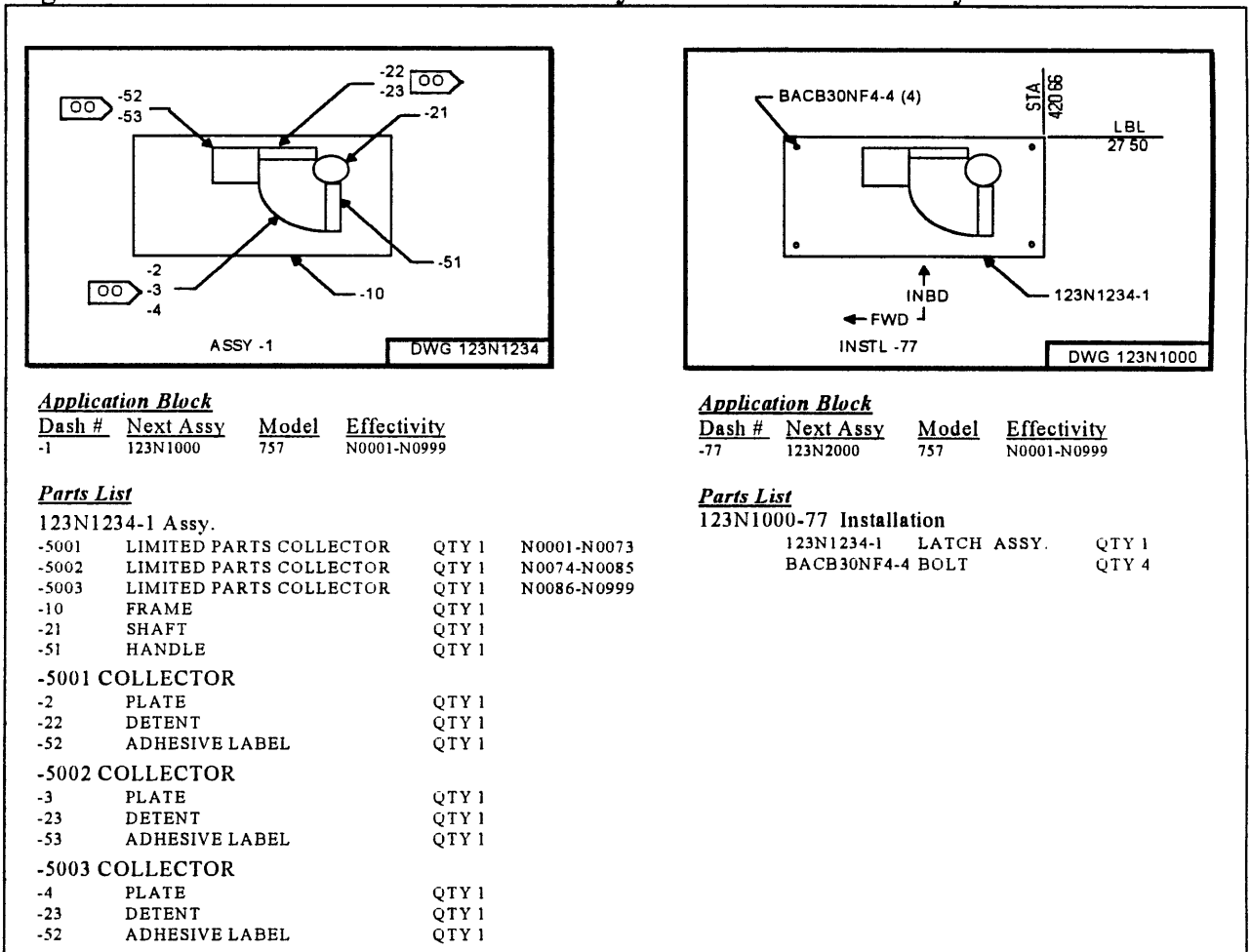
Figure 7.18 - Conversion Of Basic Assembly Drawing To A Fully Attributed Parts List.



Scenario #7: Internally limited assembly drawings “-5000 Limited Parts Collector”.

This scenario describes an assembly drawing which uses effectivity to internally limit part usage without re-identifying the assembly number.²³ These types of assembly drawings are often referred to as “-5000 drawings” or “Limited Parts Collectors”. The -5000 assembly along with its companion installation drawing is shown in Figure 7.19. The 123N1234-1 assembly defines four unique configurations. Each of these configurations are internally limited using effectivity notes in the parts lists. For example, the -5001, -5002, and -5003 parts are actually part collectors which are limited by effectivity blocks N0001-N0073, N0074-N0085, N0086 to N0999 respectively.

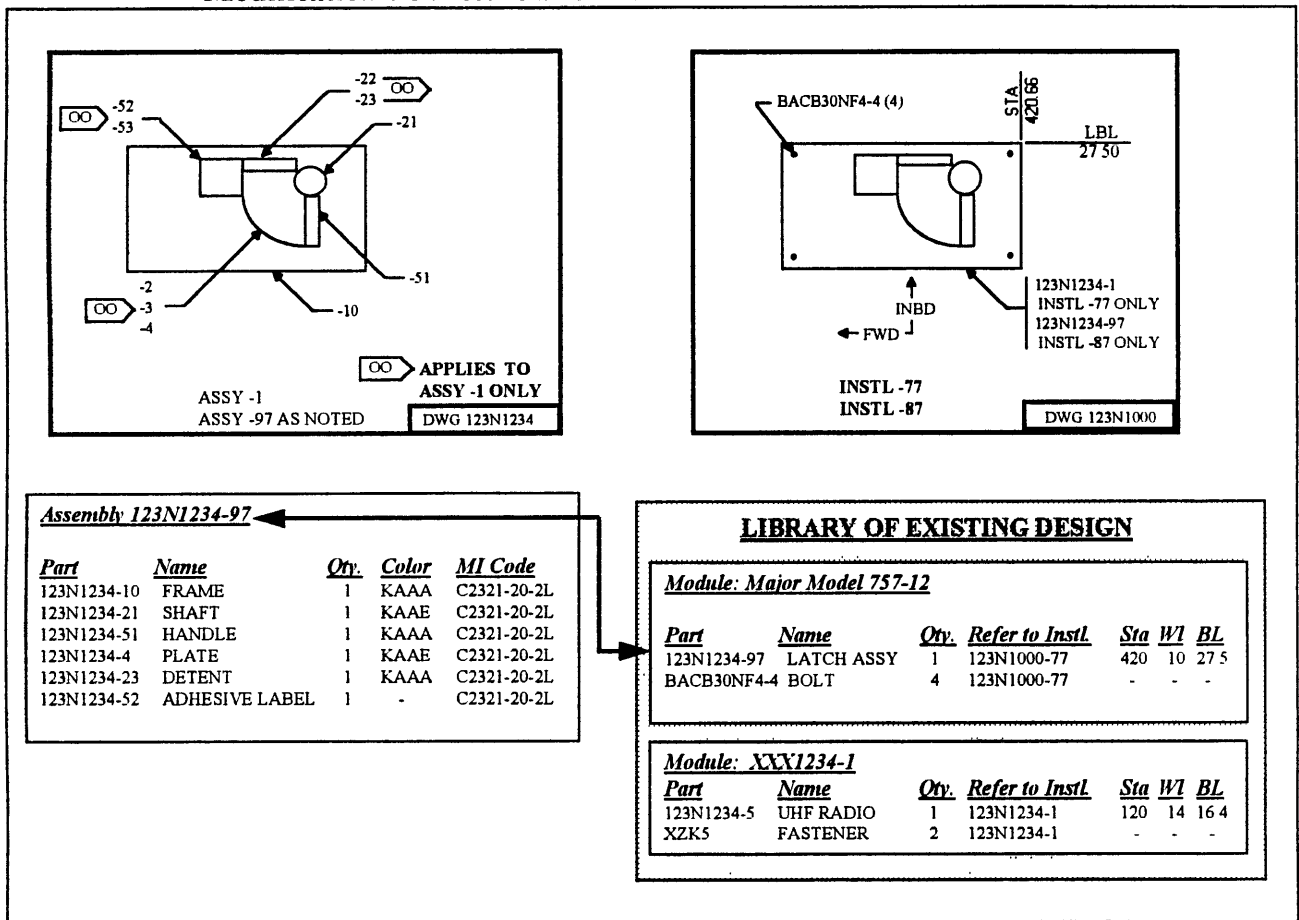
Figure 7.19 - Limited Part Collector Assembly With Internal Effectivity Limitations.



²³ The “-5000 Limited Part Collector” scenario was derived from example developed by Norm Carcass. The author is grateful for his kindness and assistance.

Conversion of this “-5000 Limited Parts Collector” requires that the assemblies drawing eliminate effectivity and re-identify unique configurations with unique part numbers. This does not require that obsolete designs be modified. Only offerable designs require conversion. Picture sheets and parts lists of the assembly drawing and the companion installation drawing are modified as is shown in Figure 7.20.

Figure 7.20 - Conversion of “Limited Parts Collector” Assembly Drawings Require Modification To Picture Sheets and Parts Lists.



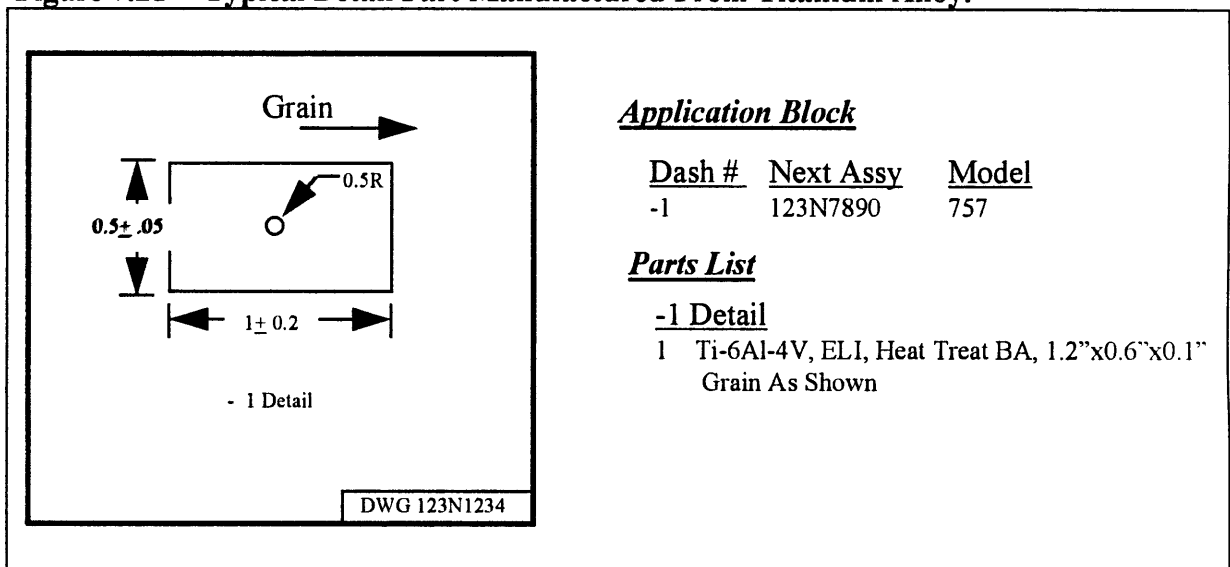
The assembly was re-identified as the 123N1234-97 assembly. The picture sheet was altered to reflect the new configuration. In addition, parts list information was modified by adding engineering characteristics data. The installation drawing picture sheet was also modified to incorporate the 123N1234-97 assembly. Finally, the 757 Major Model Module was updated with the new assembly.

Detail Part Drawings - Detail part drawings define the geometry and processes for the fabrication of the detail part. Conversion of these drawings requires few changes to the existing data. A single conversion scenario was developed for the detail part drawing.

Scenario #8: Single detail part drawing defining single part configuration

This scenario describes the engineering requirements for a plate with a 1 inch diameter hole in the middle. The plate is manufactured from a common Titanium alloy and is shown in Figure 7.21.

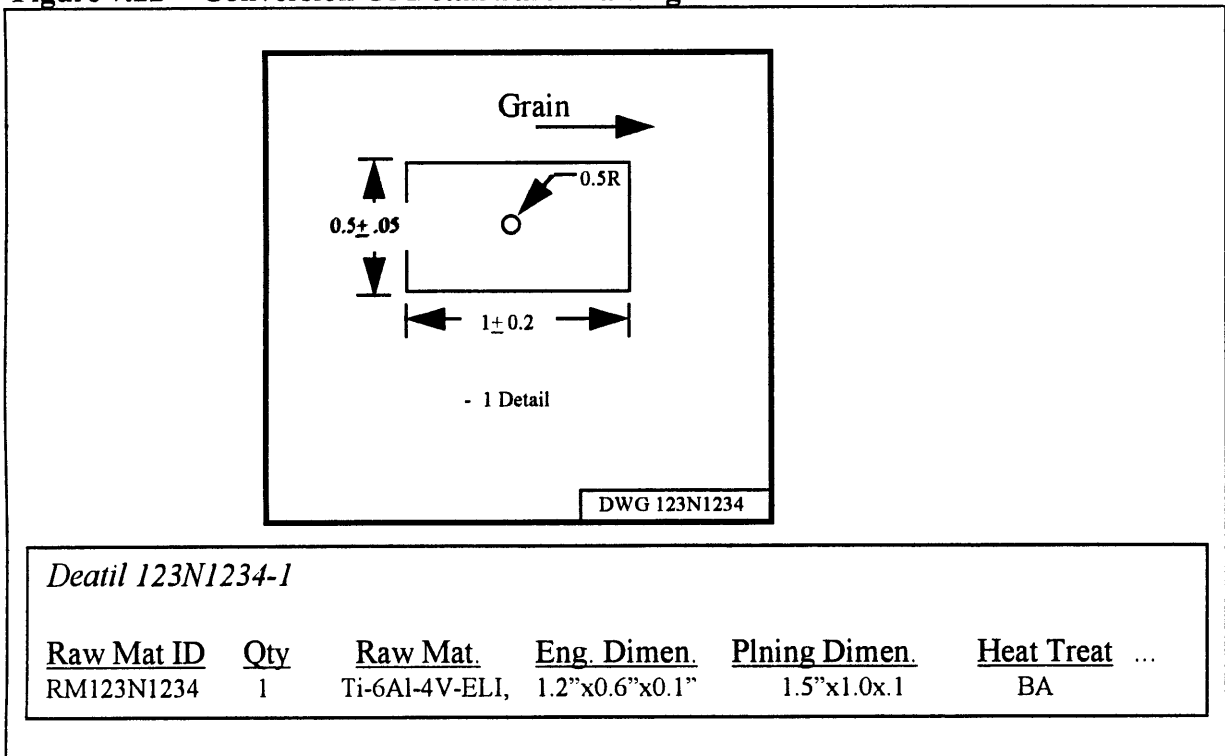
Figure 7.21 - Typical Detail Part Manufactured From Titanium Alloy.



The engineering specifies the part geometry, tolerances, material type, grain direction, and raw material with engineering excess. The parts lists defined the engineering specification for the raw material. The engineering specified raw material is then translated by the Manufacturing Engineering organization to include manufacturing excess and by the Material organization in to a 10 digit ordering code. The relationship between the engineering requirements and the order is manually maintained.

Conversion of detail parts into the module based product architecture has not impact on the picture sheet but does modify the parts list information. The converted data is shown in Figure 7.22.

Figure 7.22 - Conversion Of Detail Part Drawings Modifies Part List Data.



Part list raw material data is stored under a unique raw material identifier. The identifier contains both the material specifications from design engineering as well as manufacturing engineering. This raw material identifiers exist in a electronic library allowing the engineer to choose from a list of raw material options. This allows Material, Design Engineering, and Manufacturing Engineering to use the same data base and eliminate duplication of data and manual data manipulation.

7.2 Development Of Configuration Rules Base Is An Integral Part Of The Conversion Process

Concurrent with the conversion of the engineering data, a configuration process must be developed which identifies the correct modules in the ASCT given a complete selection of the customer options. The input to this configuration process is the functional configuration specification. The output of this process is the physical design configuration definition. Since the module based product architecture implements pure part number control, deriving the Airplane Specific Configuration Table (ASCT) completely specifies the physical design configuration of the aircraft. The configuration process must (1) derive a complete list of modules from a customer specified list of options (2) identify and populate derived assemblies.

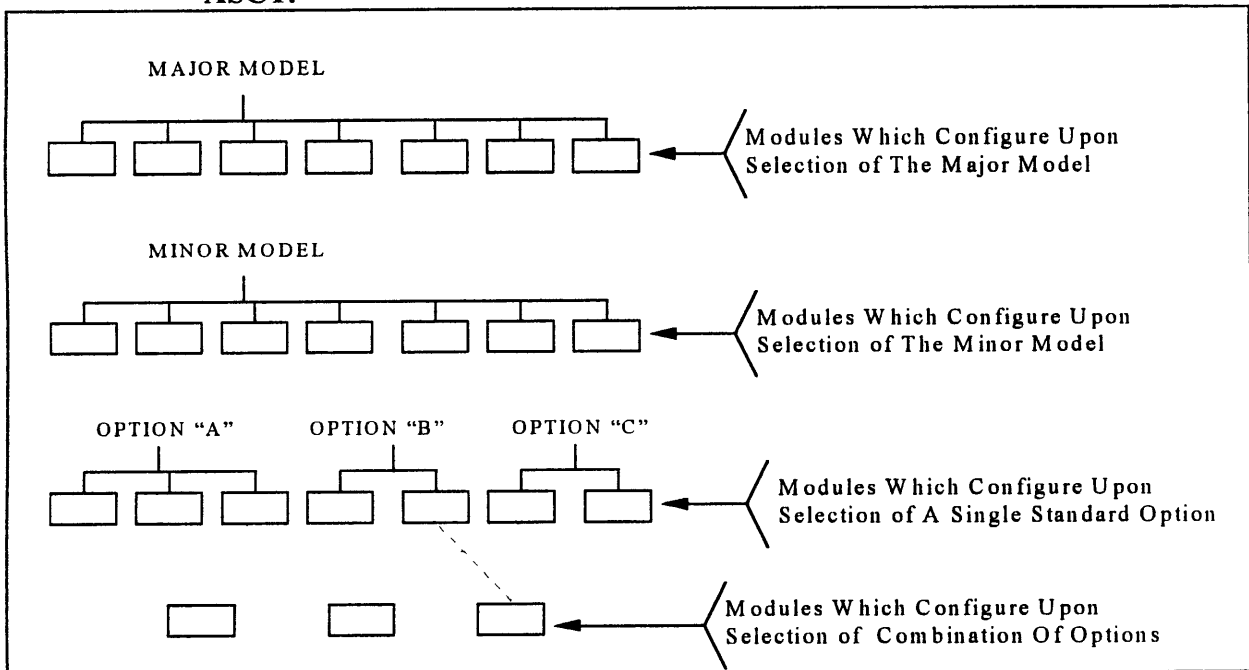
Specification of the Physical Design Can Be Accomplished With Two Basic Approaches -

Deriving the physical design from the functional configuration specification can be accomplished by using either a rules based approach or an object oriented relationship model. The rules based approach creates a decision hierarchy that explicitly defines the option to module relationship. The object oriented relationship approach models the nature of the configuration process using object classes and configuration principles.

The “rules based” approach defines the relationships between the option and the module. These basic relationships are shown graphically in Figure 7.23. For example, when the customer selects the 747 aircraft, all of the modules that are common to every 747 become active in the ASCT. In addition, when the customer selects the -400 Freighter version of the 747 (i.e. the minor model), all of the modules that are common to every 747-400 freighter become active. This part of the configuration process is relatively straight forward because of the simple and static nature of the relationships. Activation of dependent modules is a more complex activity. As described earlier, a dependent module contains part instances which configure onto the aircraft only when a combination

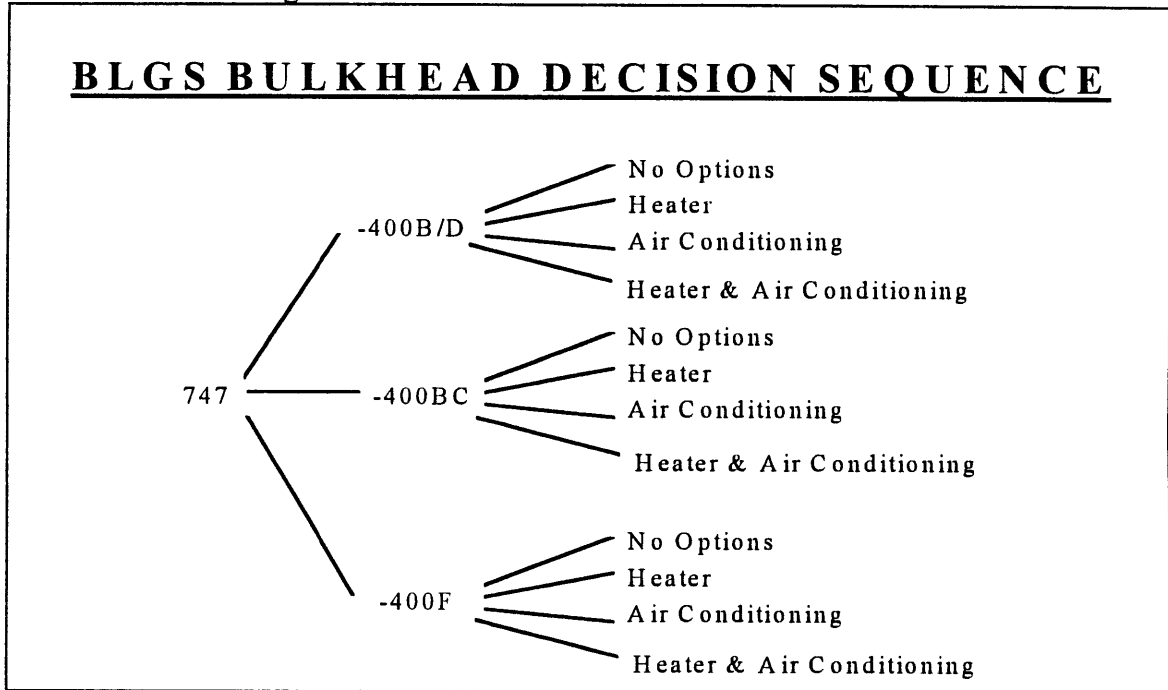
of options has been selected. Examples of this include relationships like OPTION A & OPTION B or OPTION A and NOT OPTION B. The second example pertains to parts that configures onto the aircraft only when OPTION A has been selected and OPTION B has **not** been selected. These more complex configuration scenarios require that the configuration engine utilize a full suite of Boolean functionality.

Figure 7.23 - Configuration Rules Configure the Major Model Modules, Minor Model Modules, Standard Option Modules and Dependent Modules Into The ASCT.



Consider the configuration process for the Body Landing Gear Support (BLGS) Bulkhead described in section 5.0. The bulkhead configuration is dependent on three types of options: the major module (i.e. 747), the minor model (i.e. Passenger, cargo, or combi.), the standard options (i.e. air conditioning and heating in the cargo bay) The decision sequence required to configure the bulkhead is shown in Figure 7.24.

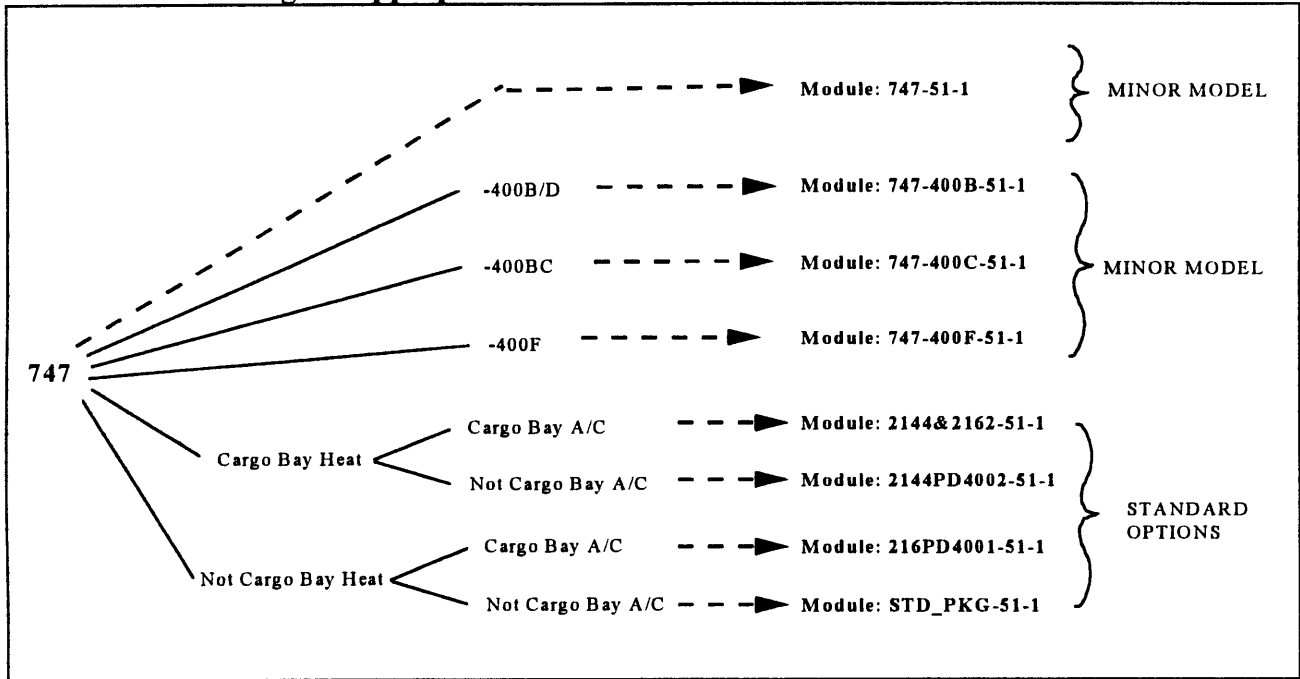
Figure 7.24 - Configuration Rules To Configure the BLGS Produce 12 Potential Configuration Outcomes.



The first node in this decision sequence identifies the major model. This activates all of the modules which are basic and stable for all 747 aircraft. The second set of nodes in the decision sequence identify the minor model. Each of these nodes activate all part which are common to the minor models for the particular major model of interest. Finally the third set of nodes in the decision sequence specifies the standard options.

Although 12 nodes are shown in the decision sequence, several of these nodes are independent of one another. For example, selection of the standard option (heater or air conditioning) is independent on the minor model. Interdependencies between modules create the configuration logic necessary to configure the “dependent modules”. Explicit Boolean rules are the foundation for the configuration computer program. The decision sequence, shown in Figure 7.24, was converted to a set of configuration rules which describe the relationship between the options and module. Figure 7.25 shows the decision network and the configuration rules.

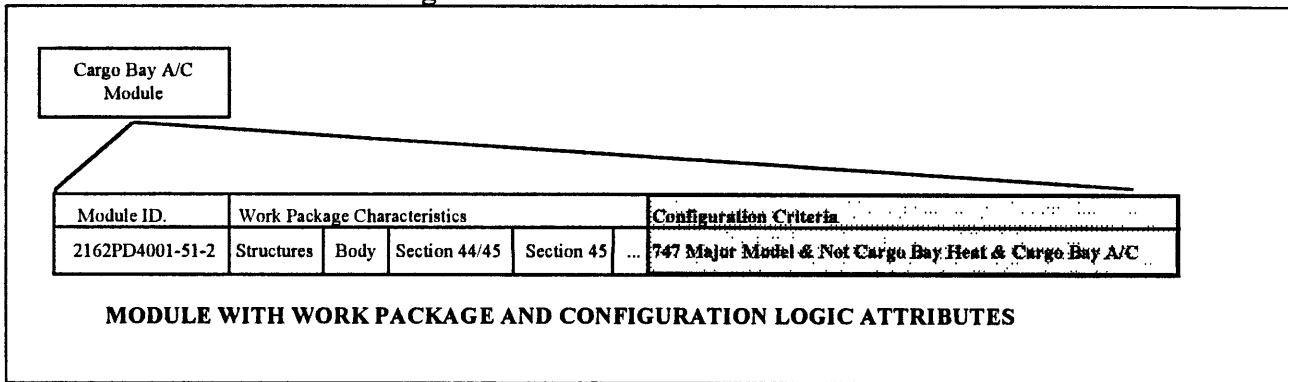
Figure 7.25 - Decision Dependency Network Reveals Boolean Relationships Required To Configure Appropriate Modules.



Activation of the "747 Major Model Module" requires selection of only the 747 major model option. However, activation of the "Minor Model Module" requires that both the major model and the minor model options be specified. Likewise, activation of the "Cargo Bay Heater and/or Air Conditioning modules require that the major model, heater and air conditioning options be defined. The Boolean expressions, shown in Figure 7.25, become the foundation for the configuration engine. The configuration engine looks for a match between the combinations of options selected by the customer and the combinations of options contained in the Boolean expression. When a match is identified, the module is activated in the ASCT.

The Boolean expressions are contained inside the module as characteristic data. Figure 7.26 shows the Cargo Bay Air Conditioning Module enhanced with the Boolean expression defining the configuration rule.

Figure 7.26 - Module Attribute Data Defines The Combination Of Options Which Must Be Present To Configure The Module Into The ASCT.



The module shown in Figure 7.27 shows the configuration criteria which must be satisfied in order to configure the Cargo Bay Air Conditioning Module on to the aircraft. For this module to be configured in to the ASCT, the following options conditions must be satisfied:

- (1) Selection of the “747 Major Model Option”
- (2) Selection of the “Cargo Bay Air Conditioning Option”
- (3) No selection of the “Cargo Bay Heater Option”

These three option selections (including the “Not” selection condition on the Cargo Bay Heater) create the Boolean logical condition which configures the module onto the aircraft.

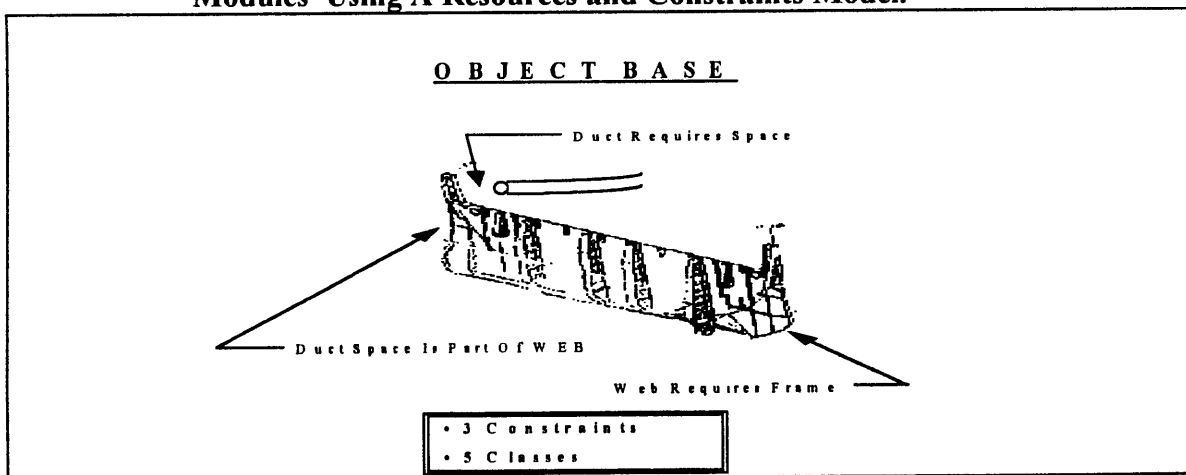
This type of rules engine is standard practice in the automobile industry. Investigations at Ford Motor Corporation and Chrysler Corporation reveal that these Boolean expressions can contain up to 15 logical conditions which must be simultaneously satisfied prior to a

part being configured onto an automobile in an assembly line.²⁴ The Ford System contains over 2.3 million parts which are configured using Boolean expressions. These expressions are continuously updated to reflect incorporation of design improvements on the line as well as the introduction of annual new product introductions.

A second basic approach for deriving the physical design from the functional configuration specification is to employ an object oriented relationship model. This approach used resources and constraints approach to derive the configuration from a set of functional requirements. For example, if a functional requirement is to configure a UHF radio into the aircraft, the “UHF radio object” requires two resources before it can be implemented: electrical power and physical space. Electrical power is supplied by a generator and power is transferred to the radio through wire bundles. Therefore, when the customer requests a UHF radio, the radio configures the electrical generators and the appropriate wire bundles. This process continues until the aircraft is specified.

The resources and constraint approach was used to create a configurator algorithm for the BLGS Bulkhead. A summary of the types of resources used in the model is shown in Figure 7.27.

Figure 7.27 - Object Oriented Configuration Model Identifies the BLGS Bulkhead Modules Using A Resources and Constraints Model.



²⁴ Discussions with Tom Sovitch at Ford and Bob Valenta at Chrysler on December 7 & 8 1995.

Physical space and structural support were the resources used to create the model. The components each provided or required different types of physical space and or structural support. The configuration process begins with the specification of a customer option. This option configures the basic end item in the aircraft. For example, customer selection of the air conditioner configured the air-conditioning duct into the aircraft. The duct was a component which required space in order to physically pass the necessary air to the lower lobe of the cargo bay. The duct space was a part of the web. The resource called duct space was provided by the bulkhead web. This brought the web into the configuration. The web requires structural support which is a resource provided by the frame. This resource requirement brings the frame into the configuration.

This type of modeling reduced the number dynamic relationships required to configure the bulkhead. However, behind the dynamic resource relationships were static relationship imbedded in the class structure of the components.

The model developed for the BLGS bulkhead was also sensitive the sequence in which the resources were requested. To eliminate the path dependence of the configuration model, rules were imbedded in the product structure similar to those used in the “rules based” approach. In summary, the resources and constraints methodology appears to provide a method to nest the static relationships in the class structure thereby reducing the total number of dynamic constraints being used explicitly by the configuration engine. However, the abstract nature of the modeling process made it difficult to non-computer programmers to understand.

8.0 OPPORTUNITY FOR ADVANCED MANUFACTURING SYSTEM MODELING

The module based product architecture enables the creation of three different and very distinct manufacturing processes which are tailored around three fundamentally different product flows. The first manufacturing process is designed to efficiently manufacture portions of each aircraft family which are basic and stable of every aircraft delivered. The second manufacturing process is designed to fabricate portions of each aircraft which have been previously designed by engineering and are implemented on any member of the aircraft family only when specific customer options have been selected. The third manufacturing process creates and fabricates new design to satisfy new functionality.

The module based product architecture creates the relationships between the option, the physical design, and the physical production configuration. This architecture aligns all “part instances” with the options that control the configuration of the parts on the aircraft. By statistically evaluating how often the option is selected, the probability that these parts will be on the next aircraft produced can be determined. Parts that are on every aircraft produced may be manufactured with a lean, synchronized production flow.²⁵ Parts which are dependent on the customer requesting a previously designed customer option and have high variability of production demand, may be manufactured using Manufacturing Resource Planning (MRP) processes. Finally, newly defined functionality which has not yet been designed are manufactured using a project planning tools together with MRP tools to develop the engineering design, plans and hardware.

Moving Boeing’s existing manufacturing system toward a manufacturing system which utilizes synchronous production techniques will require considerable analysis and simulation to determine efficient factory designs and production flows. The module based product architecture enables this simulation activity by identifying the basic and stable

²⁵ More generally synchronous production flows can be used with any parts that demonstrate low variance of production demand.

product flow and providing the information library necessary to conduct large scale simulation of commercial aircraft fabrication.

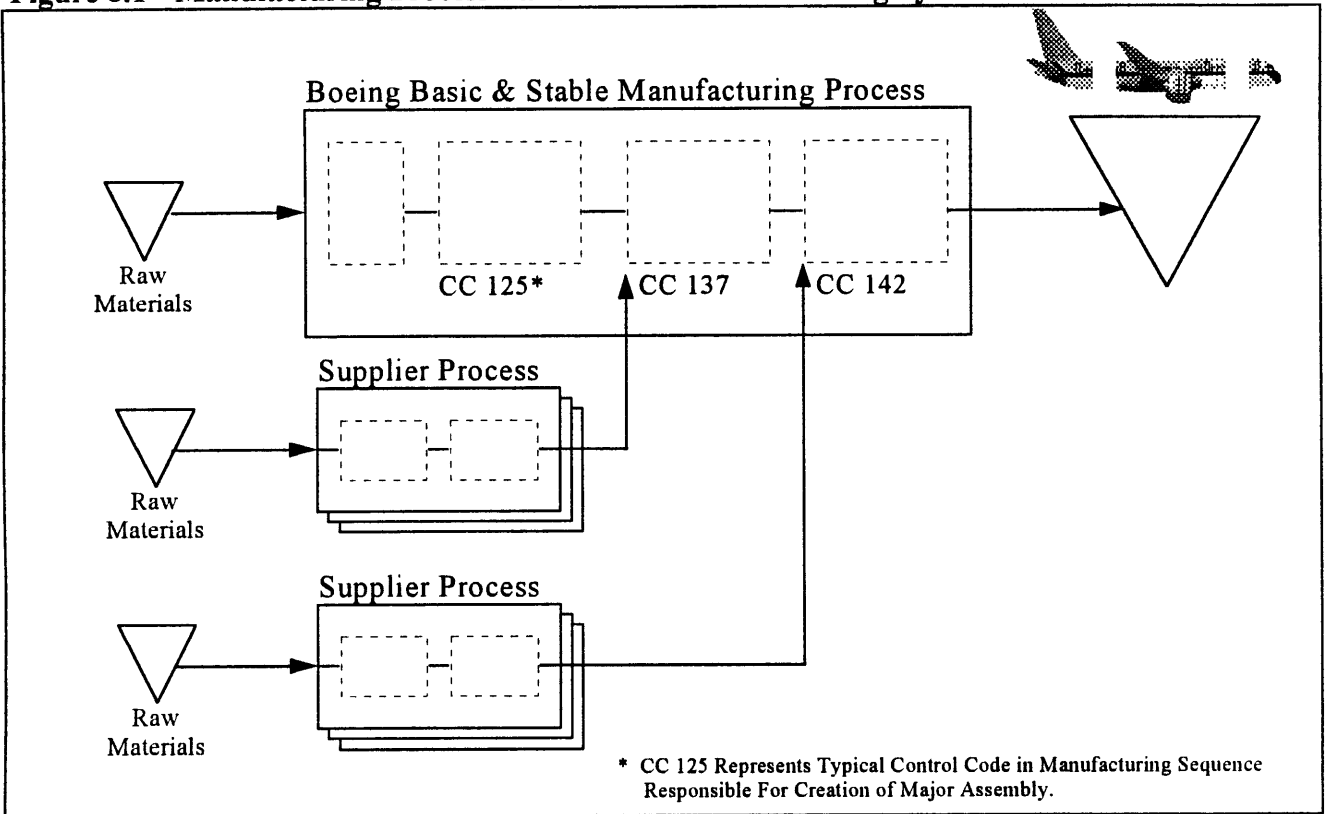
Basic and Stable Products Allow Rate Based (Synchronous) Production Techniques -

The first manufacturing process is designed to fabricate hardware which is basic to every aircraft in an aircraft family that is produced. Since aircraft are built in relatively stable rates (e.g. 4 airplanes per month), parts that appear on every airplane move through the factory at highly stable rates which are synchronous to the master production schedule. This first manufacturing process is specifically designed to build components which have highly stable production rates in the factory. Stable part and assembly production allows the manufacturing process to employ rate based scheduling tools. In this “pull production” environment, Kanban based production approaches replace costly MRP based computerized planning and tracking systems.

This production system is not limited to inside Boeing but applies to the entire supply chain. With the supply chain producing subassemblies which are synchronous to the production schedule, much of the existing inventory buffers, which are used to de-couple highly variable product flows, are not required. This allows traditional inventory based de-coupling points to be moved downstream in the supply chain as is shown in Figure 8.1.²⁶

²⁶ Manufacturing system de-coupling theory originally proposed by Oliver Scutt from Booze Allen Hamilton, November 15, 1994.

Figure 8.1 - Manufacturing Process Tailored To A Basic and Highly Stable Product Flow.

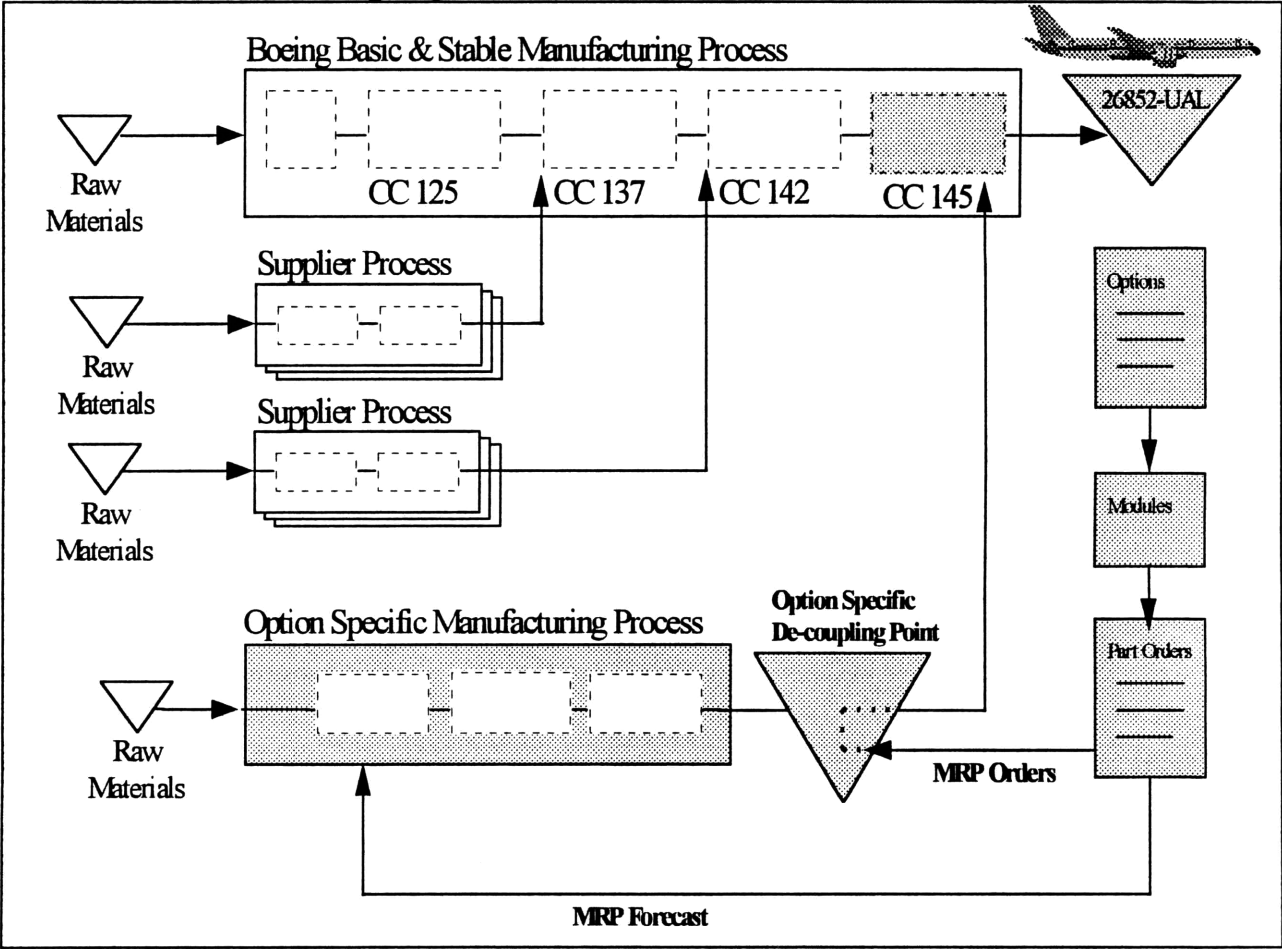


By moving inventory points downstream in the manufacturing process, a significant amount of inventory is eliminated from the manufacturing enterprise. Kanban tickets synchronize the production process eliminating the needs for complex MRP calculations. The simplicity of the Kanban system allows the gradual elimination of inventory by progressively reducing the number of total tickets in the manufacturing system.

Option Specific Hardware Manufactured By MRP Based Manufacturing Process - The second manufacturing process is designed to manage hardware which is configured on to an aircraft only when specific options have been selected by the customer. Since these

parts are used only on specific aircraft, their usage may be highly variable. Highly variable demand cannot be managed by synchronous production methods and requires the more complex MRP based scheduling and ordering system. This second manufacturing process operates concurrently with the synchronous process. These manufacturing processes are shown schematically in Figure 8.2.

Figure 8.2 - Option Specific Hardware Should Be Introduced As Late As Possible In The Manufacturing Sequence.



It is very important that the option specific manufacturing process introduce option specific sub assemblies into the synchronous production flow as late as possible in the production sequence as possible. When option specific assemblies are joined to basic and

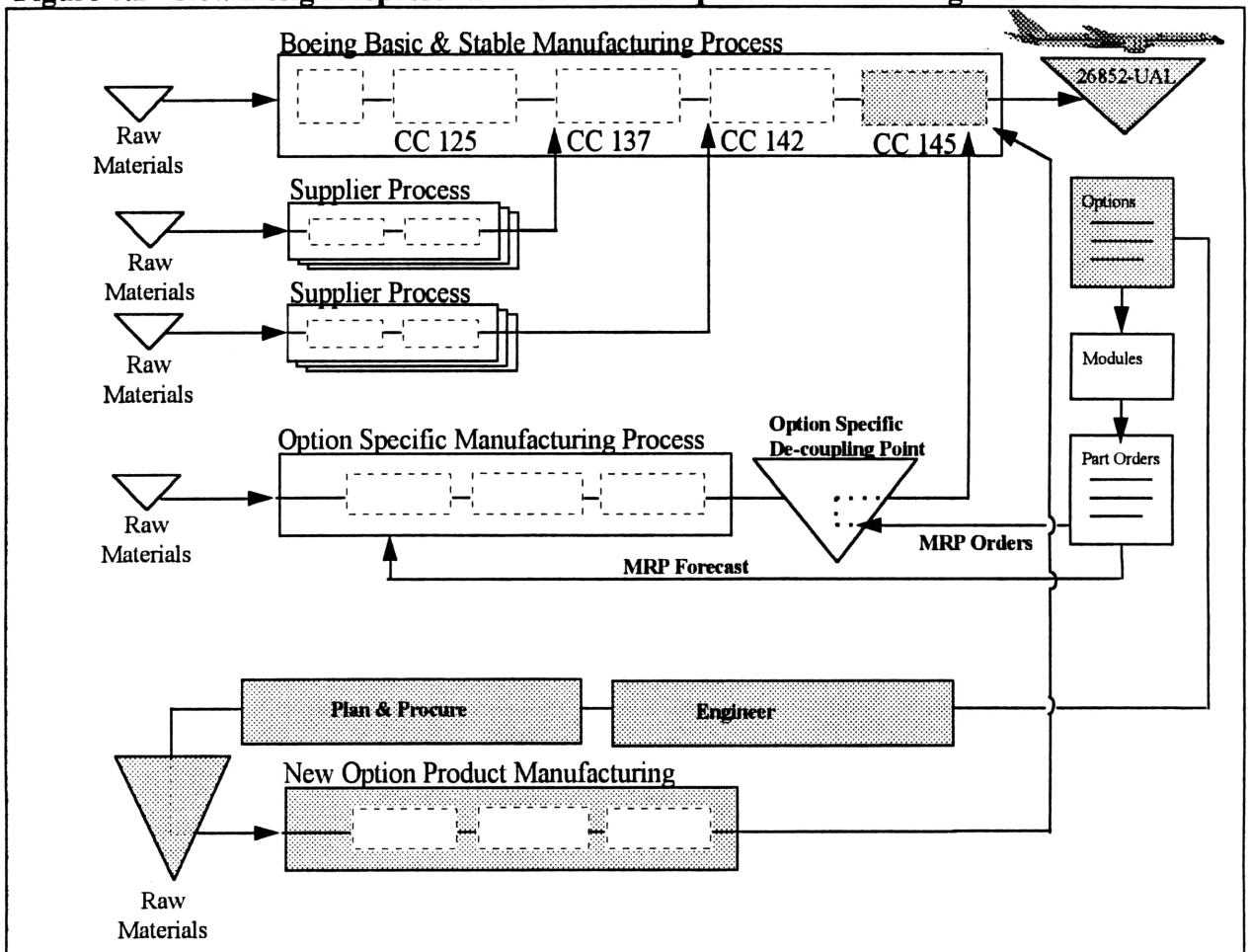
stable assemblies, the resulting assembly can now be used only on a specific aircraft. This new assembly must be treated as option specific hardware requiring MRP scheduling. Therefore, option specific product flows should be introduced at late as possible to maximize the efficiency inherent in the basic and stable manufacturing process.

Sub-assemblies manufactured by suppliers and support shops should be, as much as possible, basic assemblies that may be used on any aircraft. Deferring incorporation of options specific hardware onto these assemblies reduces the time between customer specification of a desired option and delivery thereby reducing cycle time.

Figure 8.2 shows United Air Lines (UAL) taking delivery of aircraft number 26852. United has specified a unique set of options which through the module describe all parts that must be configured to satisfy the functionality contained in this unique set of options. Parts that support these options must be accurately planned and sequenced because they can only be used on a single aircraft. The MRP system performs the necessary timing calculations and generates part orders. Orders are then filled immediately from available inventory (available inventory created from an MRP forecast) or passed to the appropriate production shop thereby signaling initiation of production. As can be seen, the MRP system is complex. Since, the level of effort required to organize and plan the option specific hardware is considerably higher than the synchronous production flow, the manufacturing system must move as much production into the synchronous production system as possible.

New Design to Support New Functionality Requires the Most Complex Manufacturing Process - The most complex manufacturing process occurs when customers requests new functionality that has not been previously designed. This process does not allow for any de-coupling and requires adequate lead time to design, schedule, procure and fabricate the necessary hardware. This third manufacturing process has been incorporated in to Figure 8.2 and is shown in Figure 8.3.

Figure 8.2 - New Design Represents The Most Complex Manufacturing Process.



Re-designing Boeing’s manufacturing system to incorporate three basic processes previously described will require re-sequencing the work flow to take full advantage of synchronous production opportunities.. New production sequences push the option specific hardware toward the last stages of production. This effort will require significant levels of manufacturing system simulation to understand the impact and performance of these new production sequences.

To understand the impact of new production sequences, discrete simulation of the production system will be required. These simulations will need detailed information at the “part instance” level. The module based product architecture enables these modeling

activities by electronically delivering to the simulation activity a complete and fully characterized list of parts which are aligned to the options they support. The nature of the data architecture provides an opportunity to create simulation models necessary to redesign the manufacturing system which maximize the number of parts manufactured in the synchronous production process, minimize inventory, reduce cycle time.

9.0 CONCLUSIONS

Boeing's current methods to define, control, and manufacture commercial aircraft are complex and labor intensive. Complex relationships between the functional specification, physical design, and production specification have created a production system which contains disconnected information flows. This situation limits the re-use of existing design resulting in extensive and unnecessary design customization. . Extensive design customization pervades the manufacturing system. It has resulted in the creation of a complex manufacturing system which often introduces customer unique variability early in the production process and severely limits opportunities to capture economies of scale in production.

This research effort demonstrates a new methodology for configuration identification and control which enables re-use of existing design while simplifying the manufacturing system. At the heart of this methodology is a new data architecture. This architecture eliminates effectivity by aligning the functional configuration specification with the physical design and production configuration specifications. This alignment creates a library of re-useable product design and manufacturing processes which are configured directly from customer selected optional features.

The foundation of this new data architecture is the module. The module creates the relationships between the customer selected option and the parts, plans, and tools required to physically implement necessary activities on the factory floor. Advances in relational data base technologies allow the module to provide the sole authority definition for the product configuration. This definition is not limited to identification of the part number but includes part location, surface finish, as well as other engineering and manufacturing information required to completely specify design and fabrication of the part.

Other results of this research effort include:

Creation of product flows which enable synchronous (pull) production. The module based product architecture creates product flows which are either (1) previously designed and basic to every aircraft, (2) previously designed and unique to a customer selected option or (3) new design. By creating the “previously designed and basic to every aircraft” production flow, variability in the product configuration is minimized thereby enabling the application of low cost synchronous production techniques. Since most of today’s commercial aircraft can be fabricated through this product flow, implementation of this data architecture represents a significant opportunity to reduce the cost of commercial aircraft manufacture.

New product architecture focuses re-engineering efforts to reduce cycle time. Aligning the physical design to the functional specification identifies aspects of the engineering design which require long lead times for manufacture and assembly. Once these parts and assemblies have been identified, highly focused design improvement activities can be pursued to reduce the cycle time from configuration specification to delivery of an aircraft to less than 6 months.

Module based product architecture simplifies the product structure enabling pure part number control. The module based product architecture eliminates collector drawings and modifies the hierarchical relationship between installation, assembly and detail drawings. These actions reduce the depth of the product structure thereby limiting the number of part numbers which must be re-identified when a part located at the bottom of the product structure is re-designed.

Module base architecture support Hardware Variability Control (HVC) Initiatives. Modules activate the parts, plans and tools. When parts, which contain “Key Characteristic” dimensions, are configured on to the aircraft, relationships contained in

the module based product architecture activate the HVC plans and data collection procedures.

Data architecture enables feature based Computer Aided Design. The part identification scheme described in this research activity can be used to identify features of a part or assembly. This allows information describing part features, which has previously been manually recorded on the drawing picture sheet, to be stored electronically inside the product architecture. The module specifies non-geometric information. The 3-D CAD data describes part or assembly. Together, these data sources reduce the dependence on the drawing picture sheet. Maintaining these data electronically will reduce the labor associated with manually modifying non-geometric information on the drawing picture sheet while improving the accuracy of the engineering specification.

Recommendations for future work

Develop simulations of basic and stable synchronous production system. Implementation of the module based product architecture will reveal, to an extent never before achieved, all hardware which is common to a family of aircraft. Today, much of the customer variability is introduced early in the production process. After conversion of the engineering data in to product modules, analysis and simulation activities should be conducted to re-align the manufacturing system to (1) introduce customer variability as late in the production system as possible and (2) institute a synchronous production system. Implementation of the synchronous will require extensive analysis to determine location and number of Kanban bins in production system, capitalization requirements and the interface between the synchronous production flow and the option specific MRP based production flow.

Convert the engineering data, define and populate part characteristics. This research has developed a module based product architecture which contains a variety of important engineering data. These engineering data are related to individual parts as characteristics

of the part (stored as attribute data in the database). This research identifies dozens of part characteristics which were selected to demonstrate the robustness of the data architecture. Part characteristics must be expanded to incorporate all necessary engineering data elements while standardizing these data elements across all aircraft models in the commercial division.

Establish company standards for parametric installations. This data architecture moves information off the picture sheet thereby creating a new form of engineering definition called a “parametric installation drawing”. Parameters used by these drawings to complete the definition of the engineering drawing are stored as characteristics to the part located in the data base. These drawings must be standardized while educating the work force on how to use this engineering definition properly.