The Boeing 777: A Look Back

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ABSTRACT
The Boeing 777 is the largest twin-engine commercial jet transport in service today. In 1990, approval to proceed with its development was contingent on defining an airplane the airlines would buy at a price Boeing could afford. Innovative processes were developed and implemented that focused on achieving customer preference and reduced program cost. These processes centered on Design Build Teams, Digital Product Definition, and Digital Preassembly. Two years after delivery of the first airplane, the data show that the processes made the 777 the preferred airplane, lowered program costs as predicted, and set new standards and expectations for the development of jet transport aircraft.

Figure 1. 777 First Flight

INTRODUCTION

The Model 777 (figure 1) is the newest member of the Boeing family of airplanes, filling the gap between the Model 767 and 747.

It can carry from 300 to 550 passengers over distances up to 7,500 nmi, depending on configuration selected, at speeds of 330 kn/ 0.84 mach. Its state-of-the-art features and technology, its award-winning interior design, and its inservice performance since first delivery in May 1995 have earned it praise and recognition from the technical community, airlines, and passengers alike.

Its most significant feature, however, is the totally new way the airplane was developed using digital technology and a "working together" philosophy to meet customer requirements at a reduced cost. This paper takes a look back at the design, the development challenge, the processes used, and how the airplane and those processes are perceived 2 years after initial delivery.

Paper presented at the AGARD FVP Symposium on "Strategic Management of the Cost Problem of Future Weapon Systems", held in Drammen, Norway, 22-25 September, 1997, and published in CP-602.

THE PREFERRED AIRPLANE

The Model 777 was conceived with the strong help of our airline customers. Eight airlines in particular, from Europe, Southeast Asia, and the United States, worked with Boeing to configure an airplane they preferred.

The result is the largest twin-engine airplane available (figure 2). It is offered as a family of airplanes with takeoff gross weights ranging from 506,000 lb to 660,000 lb in three configurations: 777-200, -200IGW, and -300, with additional growth versions under study (figure 3). The 777 is offered with a choice of engines from three manufacturers at various thrust ratings (74,000 lb to 98,000 lb thrust) depending on the requirements of the customers.

The latest materials technology is used for improved structural durability, maintainability, and inspectability, while providing a lightweight and cost-effective design.

An all-new circular fuselage cross-section offers greater flexibility in cabin arrangement and cargo carrying capability. The passenger cabin provides an open and spacious interior with a high level of seating versatility, ranging from six abreast in first class to seven or eight abreast in business class and nine or ten abreast in economy class. Lavatory and galley complexes are movable within flexibility zones to permit the airline to reconfigure the interior with minimal downtime and cost. The forward and aft cargo compartments provide 5,056 ft^3 of cargo space for both ULD containers or pallets, with 600 ft^3 capacity in a bulk cargo compartment.

Airplane systems are based on proven designs with advanced technology features added on the basis of enhanced performance, reliability, and economy.

The flight deck is designed with extensive human factors and industrial design influence to enhance pilot comfort and reduce fatigue, especially important on long-haul flights. Six large LCD displays provide flight control, navigation, engine and alerting information with improved visibility, readability, and reliability at reduced space, weight, power, and heat. New functionality is provided for display management, data communication, and electronic checklist to allow the crew to operate the airplane more efficiently.

Fly-by-wire flight controls are provided for primary, secondary, and high-lift control surfaces. The design maintains conventional control characteristics and controllers to retain existing pilot cues, with selected enhancement functions added to reduce workload.

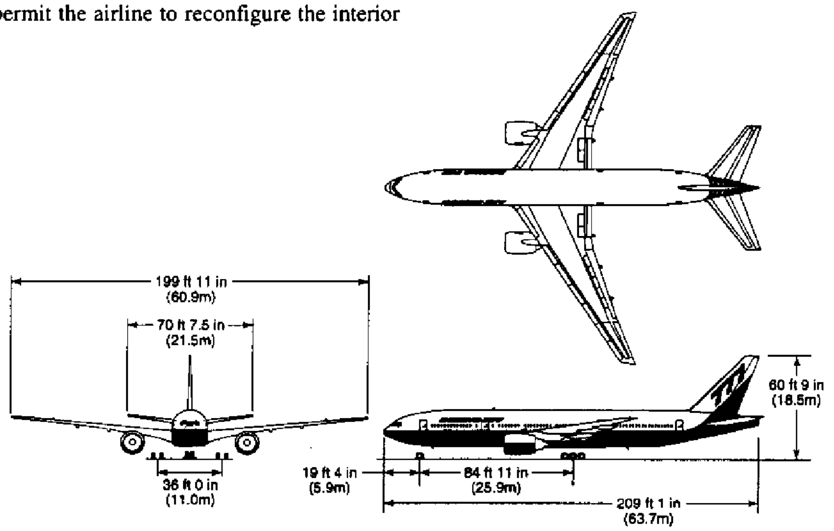


Figure 2. 777 General Arrangement

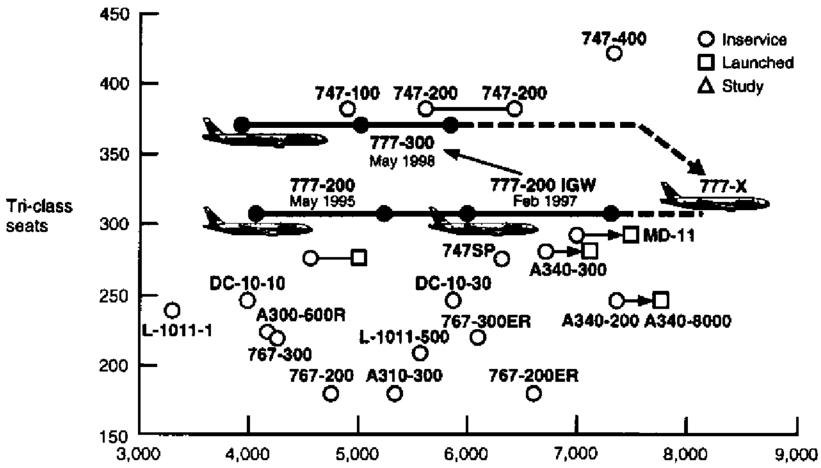


Figure 3. Family Plan

The 777 avionics include the first use of an integrated, modular avionics concept on a commercial transport. Functionality for primary displays, flight management, thrust management, control maintenance, data communication, airplane condition monitoring, and flight data recording is implemented in two avionics cabinets each with eight line replaceable modules. The four input/output modules and four core processor modules use a common hardware and software architecture. This implementation results in reduced weight and power consumption with increased reliability, simplified system interfaces, and improved fault isolation compared to federated systems. A new multitransmitter data bus (ARINC 629) permits increased communication between all systems, resulting in improved functionality, reliability, cost, and weight. Software is onboard loadable to reduce spares costs and permit faster incorporation of functionality improvements.

The electrical power system provides increased redundancy (three main generators, two backup generators, one standby ram air turbine-driven generator, four permanent magnet generators) to satisfy fly-by-wire and ETOPS requirements.

The onboard centralized maintenance system is designed with the needs of the line mechanic in mind to facilitate rapid problem resolution and return to service. Reliable, redundant systems, combined with the functionality and extensive coverage of the maintenance system, ensure our customers high airplane availability for revenue service.

THE 777 DEVELOPMENT CHALLENGE

In 1990, the Boeing challenge was how to develop an airplane that was preferred by our customers at a price they were willing to pay and we could afford to build. Key attributes included:

1. An airplane preferred over the competition because of superior functionality, reliability, maintainability, and economics.
2. Reduced overall costs, based on a 300-airplane program.
3. Service ready at delivery.

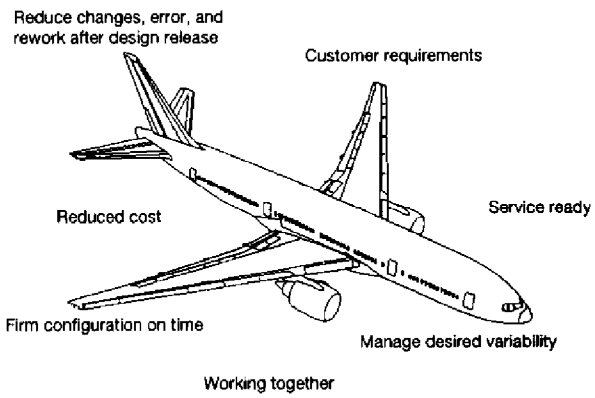


Figure 4. 777 Development Challenge

A review of past programs identified the major challenges that needed to be addressed to make the program a success (figure 4). Most fundamentally, we needed to determine what the customer wanted. This was definitely not an easy task, since requirements from multiple airlines can be quite diverse and even contradictory.

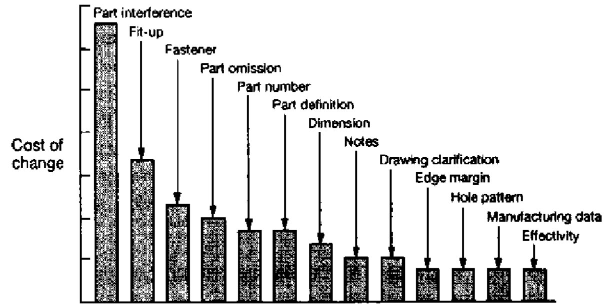


Figure 5. Traditional Cost Drivers

Change, error, and rework needed to be reduced, to reduce cost. Data showed that part interferences and fitup problems in the factory were major reasons for engineering change (figure 5). Since the cost of change increases significantly, the later the change is implemented, major cost savings would be achieved by reducing change, error, and rework after design release.

We would need to deliver a service-ready, reliable airplane on the day promised, without benefit of a prototype program. Our customers were tired of finishing the airplane development in revenue service and would only purchase an airplane that worked. Furthermore, to market the airplane successfully against three- and four-engined airplanes, the 777 needed to meet stringent reliability requirements for 180-min ETOPS (extended-range, twin-engine operations) at entry into service. This would be an industry first, since past models required 2 years of inservice experience to obtain ETOPS approval.

We would need to communicate more effectively among 4,500 engineers, 200 suppliers and 6,500 manufacturing employees. This communication would be vital to reduce change, error, and rework due to late or incomplete design information.

This resulted in a program development plan (figure 6) that focused on the following:

- Involving the customer to define the preferred airplane.
- Ensuring that all parts are designed to work and fit together before release, for 50% reduction in change, error, and rework.
- Working together to share facts and data and resolve issues.

These goals were implemented by "preferred processes" that were at the heart of the 777 Program:

- Design/Build Teams.
- Digital Production Definition.
- Concurrent Product Definition.
- Digital Preassembly.
- Enhanced Validation.

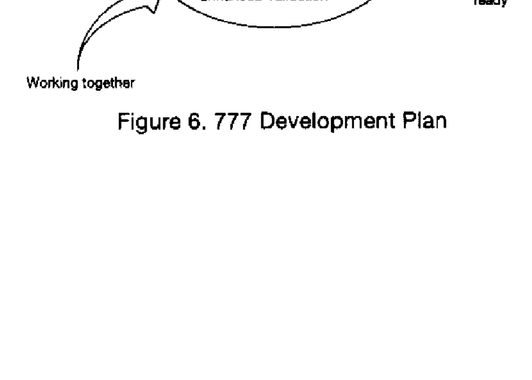


Figure 6. 777 Development Plan

DESIGN/BUILD TEAMS (DBT)

Development of a jet transport is a large and complex task involving many organizations in many locations. This largeness and complexity create their own set of problems. Activities tend to be conducted in series with results "thrown over the fence"; communication is incomplete with not all facts and data available for consideration; interorganizational rivalries and misunderstandings arise and take priority over what is best for the product.

This is further aggravated by increasing product complexity and job specialization, which result in no single person understanding all aspects of the development task. In addition, time intervals of up to 15 years between new programs makes the experience of the development team a key concern.

The 777 program countered these problems with a process of working together in design/build teams. Each team comprised Engineering (Product Definition), Manufacturing (Plans, Tools, Fabrication, Assembly), Materiel (Outplant Production Procurement), Customer Services (Training, Spares, Maintenance Engineering, Field Service Engineering), Quality Assurance (Plans, Inspections, Records) and Finance (Design to Cost) and often included supplier and airline representatives. This ensured that all facts and data with respect to functionality, producibility, maintainability, affordability, and customer preference were available for the best possible decision prior to design release. This process, implemented by program direction and extensive training and continuously reinforced, encompassed Boeing, its suppliers, and customer airliners.

Each DBT was the primary organizational entity and was responsible for the parts, plans, and tools definition of one area of the airplane. The teams were organized along traditional engineering functional lines, with members assigned to the team by their home organizations (figure 7). Each team was co-led by Engineering and Manufacturing. Higher level integration DBTs for each function ensured functional integration across the airplane, aided by integrated schedules and integrated work statements. An independent Zone Management organization was used to validate cross-functional airplane-level spatial integration (figure 8).

Full-time team members were collocated to facilitate communication. Regular DBT meetings were held with all members present to review progress to the plan and resolve any issues or concerns. At the peak of the design effort, 238 DBTs existed.

When the program shifted to the build phase, Manufacturing Integration Teams (MIT) were formed in addition to the DBTs to resolve manufacturing issues.

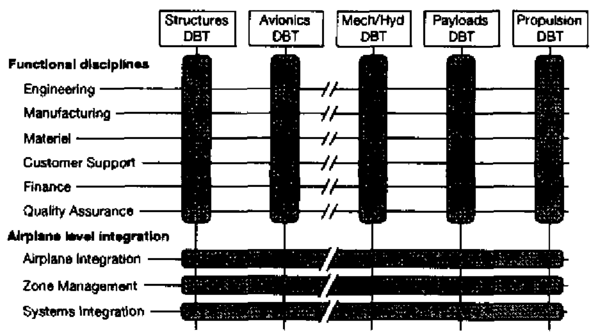


Figure 7. 777 Design/Build Team

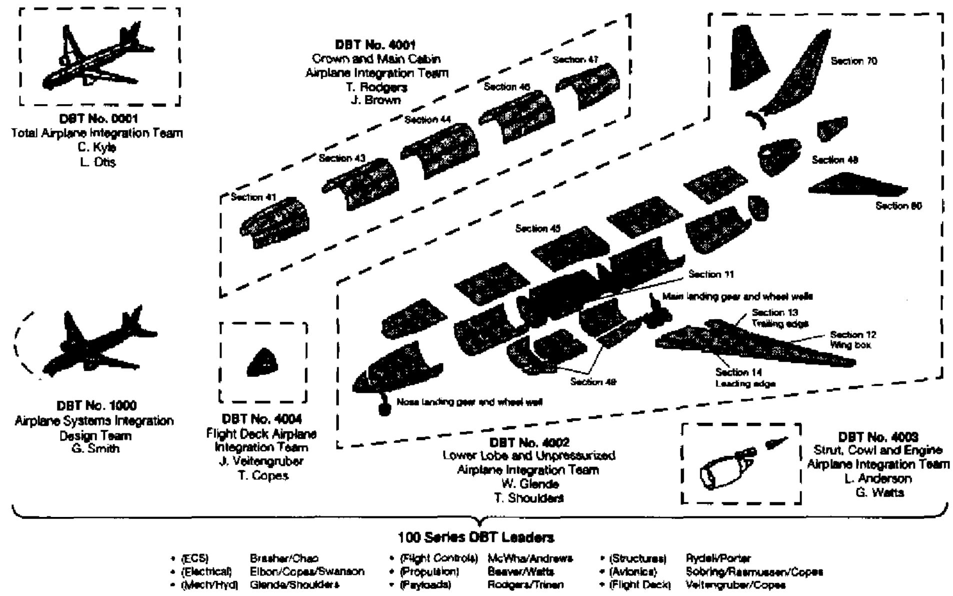


Figure 8. 777 Airplane Integration

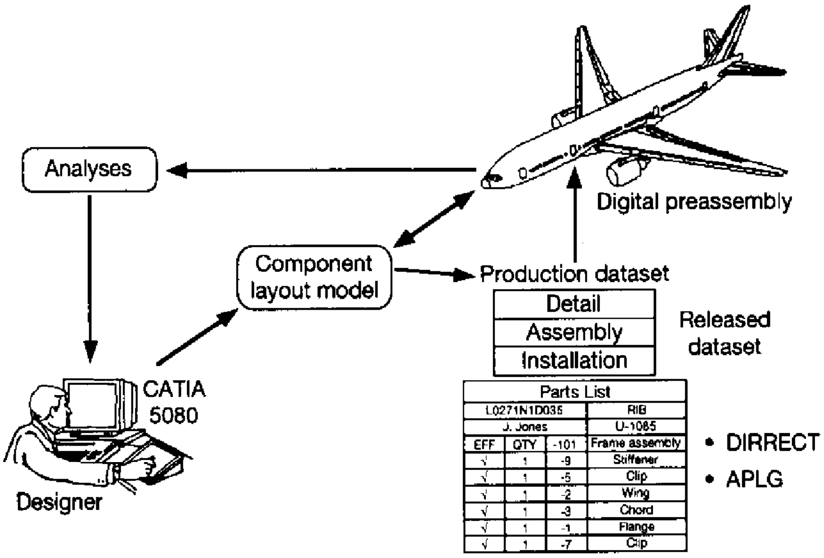


Figure 9. Digital Production Definition (DPD)

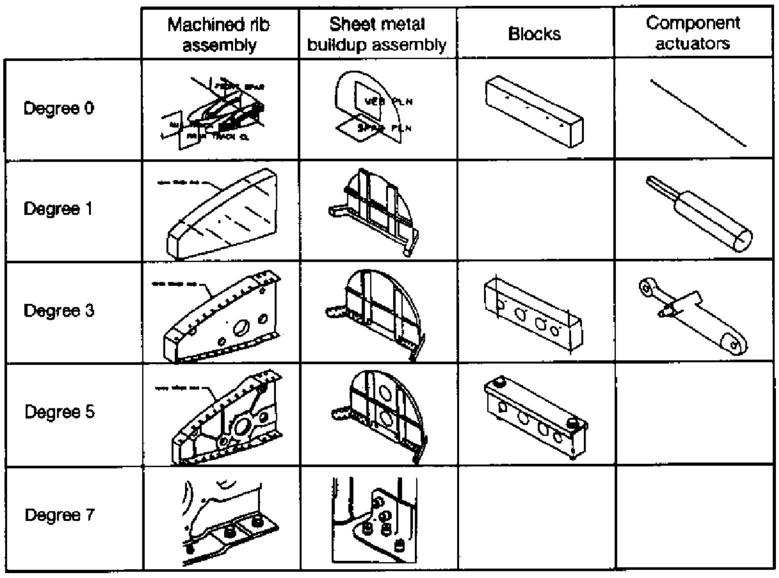


Figure 10. Digital Preassembly (DPA)

DIGITAL PRODUCT DEFINITION (DPD)

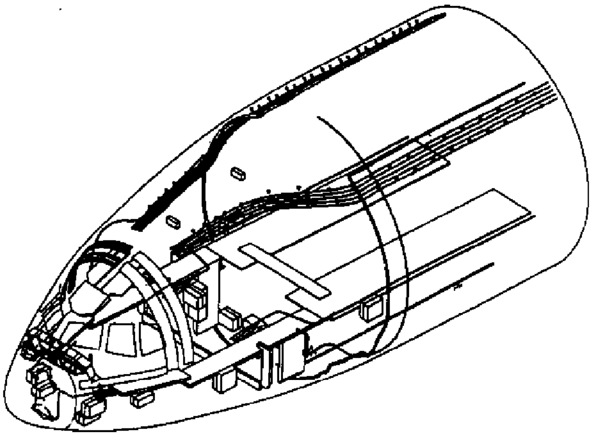
A key benefit of digital product definition is the ability to electronically assemble and analyze the airplane, thereby allowing earliest identification of interference, separation, or access problems. Additional benefits arise from the enhanced data usage by other organizations such as Stress, Weights, Tool Design, or Training. The program standardized on CATIA (Computer-Aided Three-Dimensional Interactive Application) from Dassault Systems, using approximately 2,200 individual workstations linked to eight mainframe computers in the Seattle area. This mainframe cluster also linked to installations in Japan, Wichita, and Philadelphia.

The design process (figure 9) required the engineer to develop his design in a working file on CATIA. Starting with preliminary layout models in airplane coordinates, the design was continuously shared with the 777 Team for digital preassembly. The fidelity of solid-model development (figure 10) increased with time, starting with simple envelope models (degree 1) and ending with a manufacturing-quality model (degree 5). The layouts evolved into individual details, assemblies, and installations that were released to manufacturing. Each digital release included a 3D solid model, 2D drawing data, and a bill of material, in addition to specific manufacturing requirements such as flat patterns or wire frame models. Approximately 90,000 datasets were released.

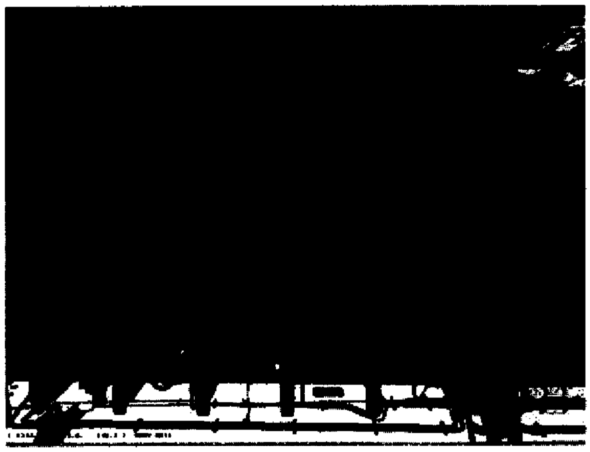
The single source of (digital) Product Definition was used by the various DBT organizations to ensure that the design satisfied their specific requirements. Manufacturing processes used the data in the area of assembly sequence planning, tool design, and production illustration development, as well as numerical control machine tool programming. Customer Services benefited in the preparation of maintenance documentation, ground support equipment design, and training aides.

DIGITAL PREASSEMBLY (DPA)

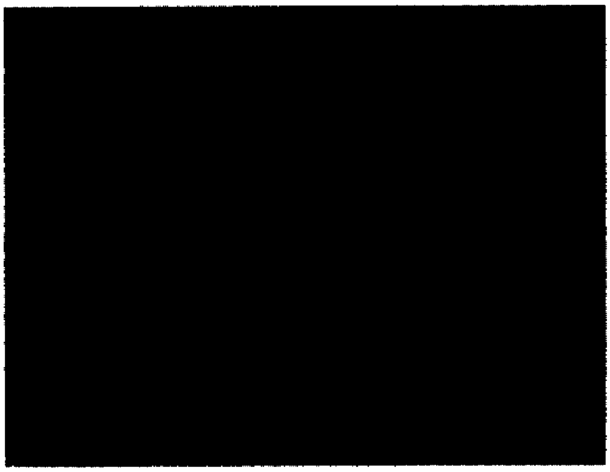
DPA consists of assembling the digitally defined parts into an airplane in order to verify proper design before release. This process eliminated the need for a physical mockup, yet allowed frequent and early design verification. Parts were assembled as needed by designers, analysts, planners, or tool designers, showing the complete airplane volume or only the parts of interest (figure 11). The designer was responsible for frequent sharing of the model, as well as conducting interference checks and incorporating design feedback from other organizations. DPA used two dedicated organizations to manage the digital preassembly. DPA administration provided data management of the share models to facilitate easy access, while Zone Management ensured cross-functional integration of the design through independent design reviews. Integration reviews were held frequently, with five formal reviews during the 2-year design phase. The reviews consisted of a cross-functional review of a particular airplane volume and were chaired by the Zone Management organization. Reviews covered functionality, producibility, and maintainability, including interference checks, interface coordination, and installation/removal access.



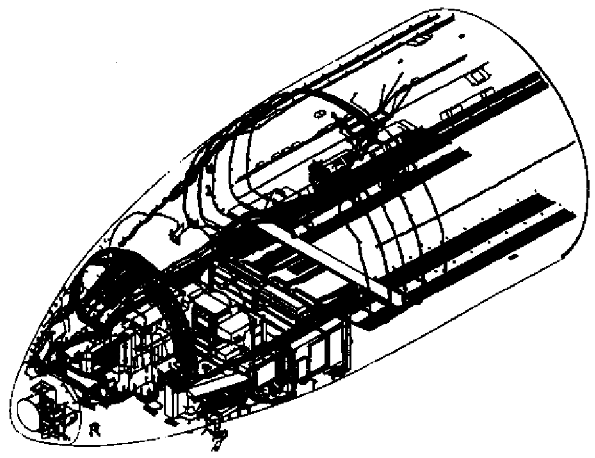
Stage 2
Section 41—Wires/electrical



Fly-Thru software
CATIA image



Full-motion human modeling
CATIA image



Stage 4
Section 41—Electrical

Figure 11. 777 Digital Preassembly

CONCURRENT PRODUCT DEFINITION (CPD)

The purpose of CPD is to define complete and integrated designs, manufacturing plans, and tools prior to release of any product definition, in order to lower the cost of manufacturing and support. This required a strong team sharing information and working together to define the product, including simultaneous design of structures and systems, analyses to support the design, production plans definition, design of critical tooling, and ground support equipment and technical publications development (figure 12). Because these activities were highly interdependent, integrated work statements and integrated schedules were used to coordinate the various tasks. This planning and scheduling activity was facilitated by dividing the program into stages (figure 13), with program and DBT goals defined for each stage.

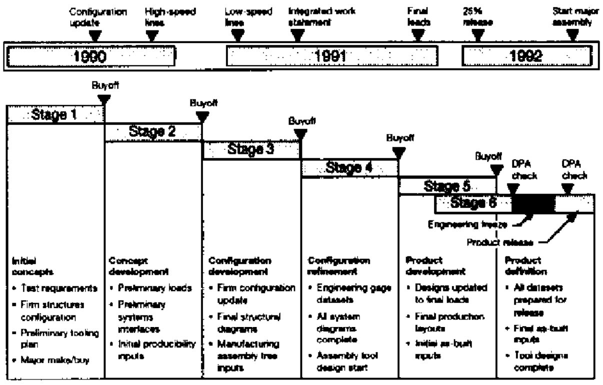


Figure 13. 777 Design Stages

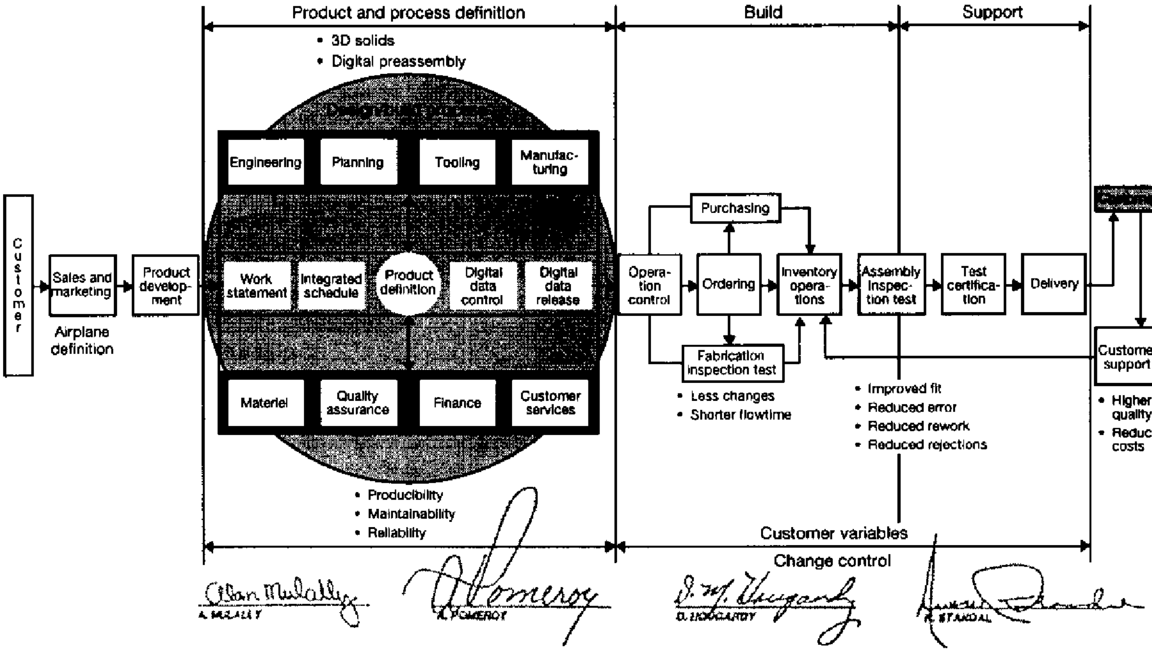


Figure 12. Concurrent Product Definition—Preferred Business Process

ENHANCED VALIDATION

A key requirement for the 777 was to be service ready at delivery, or in our customer's words, "Everything works." This resulted in an enhanced validation program compared to previous models (figure 14).

Early on, an extensive "lessons learned" activity was conducted. Service history was examined to identify existing problems and their root cause; design solutions were then identified to ensure no repeat of the problem on the 777.

Verification and validation analyses were greatly expanded to minimize problems during the lab and flight test phases (figure 14). Digital interface reviews were conducted for each LRU and its member systems to ensure that data and logic flows were understood for all flight phases and operating states. Airplane-level analyses ensured that each function, such as stall warning, was correctly implemented by all subsystems under all operating scenarios as well as normal and failure conditions. Flight deck message reviews were held to ensure that we had implemented the minimum number of messages and that those messages worked correctly. Airplane-level failure analyses went beyond the normal single-system analyses by examining the total airplane effect of single and multiple failures. Operational analyses were led by the pilot community to validate all normal and non-normal procedures.

Lab testing was expanded for both qualification and validation. Equipment qualification testing included "test to failure" conditions to identify and fix weak points in the design. In addition to the standalone and system test facilities, a systems integration lab was used to test the electronic systems. The lab was configured to spatially represent the airplane and used production power generators, wire bundles, electronics, and flight deck components. Simulation of airplane dynamics, environmental conditions, and mechanical systems allowed realistic testing by flight test pilots who performed each test as an actual flight (figure 15).

APU and engines were each subjected to a 3,000-cycle ground test to demonstrate their service readiness, in addition to the normal development and certification tests.

Structural tests included a full-scale static load test and a structural fatigue test. The static load test vehicle was used to demonstrate limit load capability and then tested to wing destruction to determine available margins for growth. The fatigue test vehicle is being tested to three life times, completing a typical flight profile approximately every 4 min, 24 hr a day.

The flight test program used a five-airplane test fleet to validate the design. With first flight in June 1994, development testing had to be essentially complete by November 1994 to support the beginning of a special 1,000-cycle validation program. This test was in support of ETOPS certification and operated the airplane in simulated revenue service (figure 16). A key requirement was that the airplane had to be in production configuration and test results would determine ETOPS approval.

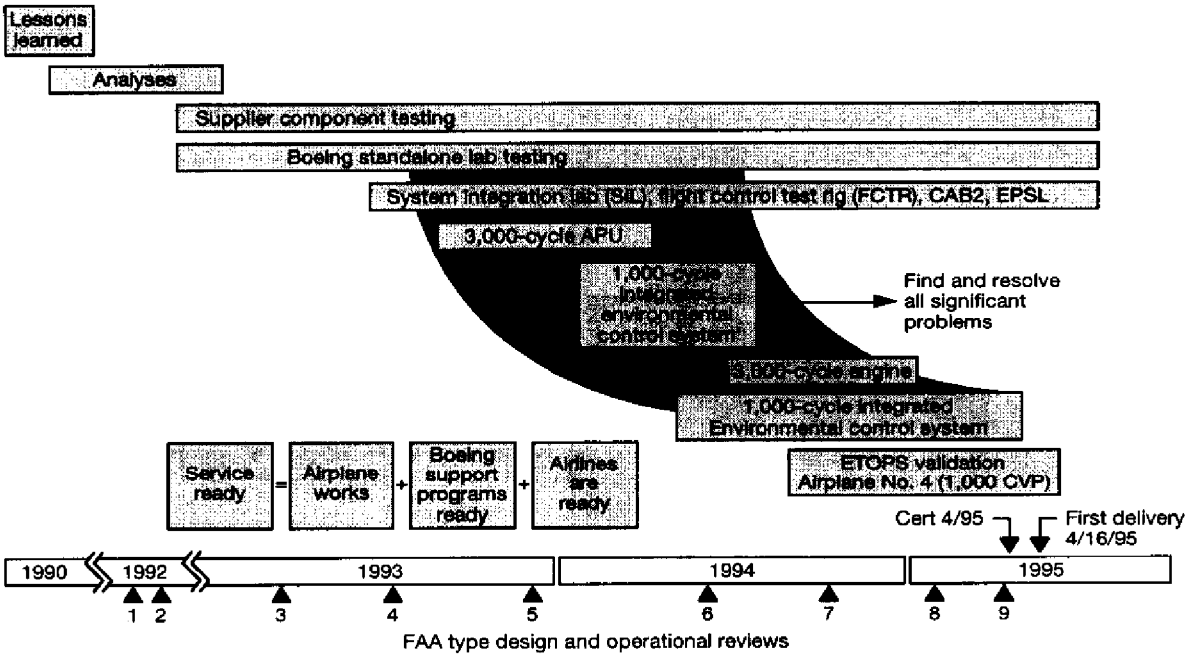


Figure 14. Service-Ready and ETOPS Certification

Figure 15. Systems Integration Lab

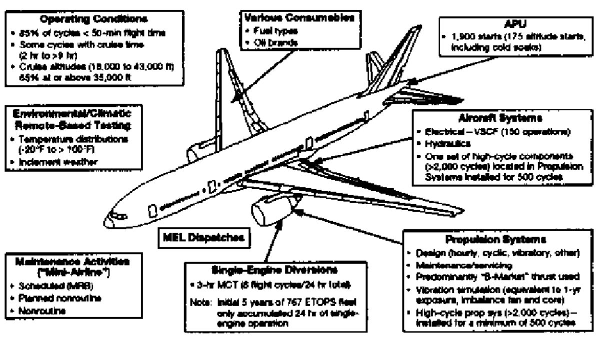


Figure 16. Validate the Airplane—1,000 Cycles and 1,400 hr

A LOOK BACK

It is over 2 years since the first 777 entered revenue service. Since that time, 95 airplanes have been delivered to 14 airlines and have accumulated in excess of 250,000 flight hours; three new Boeing derivative programs (737 Next Generation, 757-300, 767-400) have had the option of implementing the 777 processes or rejecting them. So, with all this time and experience behind us, is the Boeing 777 and its development process a success? I believe the answer is a resounding "YES!"

Industry certainly agrees, having recognized the 777 program with three awards:

1. The 1995 Collier Award for top aeronautical achievement.
2. The 1995 Smithsonian Computerworld Award for digital definition and preassembly in manufacturing.
3. The 1996 Smithsonian National Air and Space Museum Award for designing and building the most advanced and service-ready twin-engine jet in commercial aviation history.

Our customers, the airlines, clearly think so, having made it the preferred airplane. The 777 has achieved a 69% market share to date and is the single best testament to the perfect blending of functionality, reliability, and affordability. Pilots, flight attendants, and mechanics alike are enthusiastic about this airplane, as they should be, since it reflects so many of the features they requested through the working together process. I think Mr. Gordon McKinzie of United Airlines summarized it best: "Is this a great airplane, or what?"

Total program costs have been reduced when compared to a "business as usual" approach. These savings are primarily due to lower recurring costs from reduced change, error and rework by Engineering and Manufacturing. Comparisons with the 767 show approximately a 60% to 90% reduction in all change categories and fitup problems (figure 17). This results in less reengineering, less replanning, less retooling, less out-of-sequence work, less fleet retrofit, less warranty costs, lower inventory costs, less scrappage, less manufacturing flow, or, simply put, LESS COST! On the negative side, nonrecurring costs were increased due to the development and implementation of new tools and processes. Overall, however, a 15% to 20% savings in program cost is projected for the 777 (figure 18).

The airplane has demonstrated its service readiness, with a fleet average schedule reliability in excess of 98.6%, the best of any jet transport in its class at an equivalent time period (figure 19).

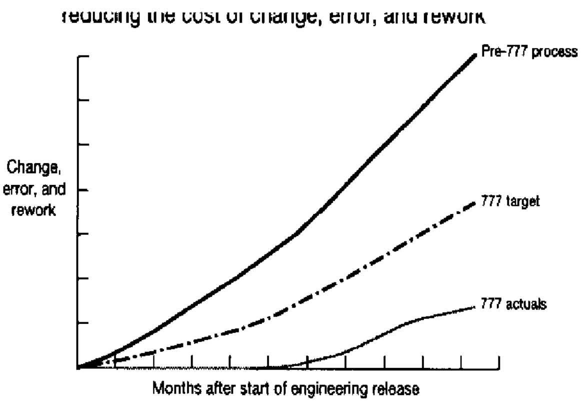


Figure 17. 777 Program Success

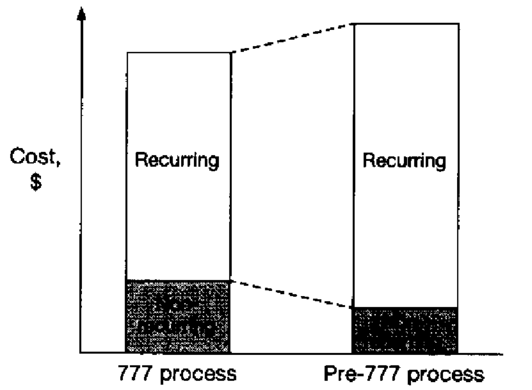


Figure 18. Program Cost Comparison—777 Process Versus Pre-777 Process

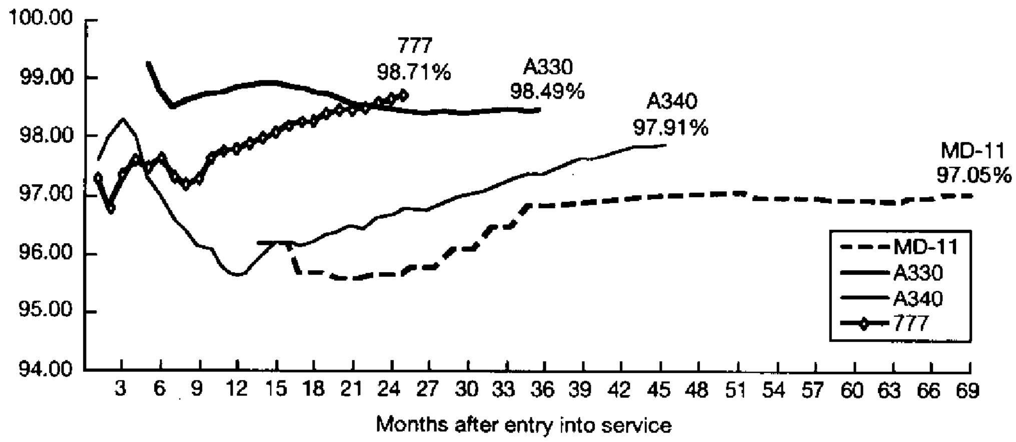


Figure 19. Entry Into Service Schedule Reliability—777, A330, A340, and MD-11 12-Month Moving Average

The 777 program success was made possible by the innovative way the airplane was developed. The specific processes used on the 777 have been carried over to the latest Boeing programs and will undoubtedly contribute significantly to their success.

The Design/Build Teams embodied the working together spirit and were absolutely essential to the success of the program. The teams brought together a wealth of knowledge and experience that no single individual had and thus permitted better decision making. Airline team members were especially effective, bringing their "real world" perspective to the team. It is a powerful process that generally became the magic solution to all problems. Technical or organizational issues were invariably solved by re-establishing or strengthening the working together activity.

Teaming does not, however, appear to be a natural human characteristic and did require training and continuous reinforcement and nurturing to prevent regression to the more individualistic attitudes.

Subsequent programs like the 737 Next Generation and 777-300 have recognized the importance of teaming to achieve reduced change, error, and rework, and hence cost, and have implemented a modified version with integrated product teams (IPT). IPTs are also cross-functional teams, but aligned by airplane volume, compared with DBTs, which are cross-functional teams aligned by commodity. While the IPT facilitates spatial integration, it complicates the functional and airplane-level integration that cross as multiple IPTs. The real key is not what the teams are called or how they are organized, but **WORKING TOGETHER** (figure 20).

Digital Product Definition (DPD) was the foundation for Digital Preassembly and was hence critical to meeting cost goals. It was essentially a totally new process that had been first used 4 years earlier in small pilot programs, such as to design hydraulic tubing for the 747-400 empennage. Significant training was required by all 777 team members to live in this new environment. DPD was found to place a significant burden on engineering, requiring approximately 60% more effort to develop a digital dataset than the equivalent 2D drawing. This was in part due to slow computing tools, where computer response time was sometimes measured in minutes. In addition, Engineering also became responsible for multiple models (e.g., solids, and wireframe) to satisfy requirements from downstream users. Lack of associativity between models further aggravated Engineering resource requirements. We also discovered that some outside suppliers did not have the capability to take advantage of the digital data in their manufacturing process. In spite of these early learning pains, DPD has become the accepted standard with the DPD "penalty" reduced to less than 10%. The use of faster computing tools and associativity between models, as well as knowledge-based product definition (automated design), is bringing us rapidly to the point where DPD, in its own right, is faster and cheaper. DPD will also form the basis for functional integration tools to reduce change, error, and rework, as well as risk, from systems interface and logic problems.

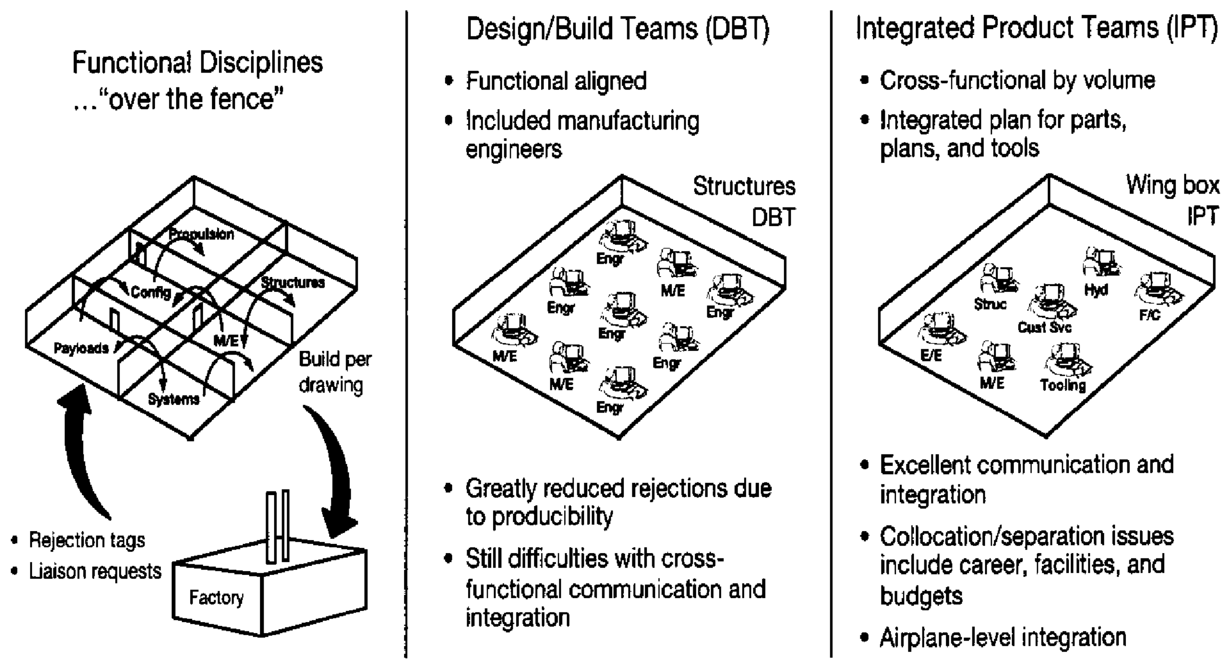


Figure 20. Evolution of Working Together

Digital Preassembly (DPA) at the airplane level was totally new and; learning how to use it effectively required significant on-the-job learning. With the introduction of Fly-Thru software, design reviews of the installation became very effective and in fact became the key means of ensuring cross-functional communication. While early emphasis was on interference checking, DPA rapidly came to be used to also check for producibility, maintainability, and safety. DPA did result in significant improvements in reducing interference and fitup problems in the factory. The assembly and installation of structures and systems is significantly easier and results in not just reduced cost, but also reduced cycle time. On a typical 777, four or five hydraulic lines out of approximately 1,700 require rework due to fit-up problems, compared to hundreds on a nondigital model.

Concurrent Product Definition (CPD) was used relatively successfully to minimize change, error, and rework. An integrated schedule was an absolutely essential tool in support of this process. Development was a complex cross-functional task that required detailed knowledge of what data are required to start a task, what follow-on activity the task supports, how long it will take, and the required completion date. System development plans, which were mandated early in the program, were very helpful in this regard. In spite of the emphasis on CPD, we did experience occasions where many design hours were spent refining installation only to start over because of late requirements, late analyses, or missing interface data.

Enhanced validation contributed significantly to reduced costs and service readiness. Numerous problems were identified early on by analysis, avoiding the much higher costs of fixing problems in test or in production.

Component and system testing in the lab further identified issues that reduced flight test risk and test time and provided sufficient time to correct the problems prior to delivery. The systems integration lab was particularly beneficial in identifying wiring and interface issues for electrical and avionics systems, as well as permitting dry running of airplane functional tests and flight test conditions.

The validation activity culminated in the most extensive flight test program ever. In nearly 1 year of flying, the P&W-powered 777 completed almost 1,600 flights for 3,600 hr. With a requirement to have essentially production hardware and software support the 1,000-cycle ETOPS program in November 1994, however, it was really the extensive analysis and lab testing that enabled us to meet the service-ready and ETOPS objectives.

CONCLUSIONS

The development of the Boeing 777 faced a significant challenge at its inception: how to create an airplane that was truly preferred by the airlines, at a price that was affordable. The program focused on two simple but powerful strategies: **working together and reducing change, error, and rework**. We used new and innovative tools and processes to implement these strategies. Looking back at the program today, 2 years after first delivery and 7 years after program go-ahead, it is clear that the two strategies produced a truly great airplane and forever changed the culture and processes at Boeing. The program laid the foundation for further improvements in tools and processes that will allow future programs to achieve even greater benefits in customer satisfaction and reduced costs.