Advanced Skills Required for Engineering Leaders in Global Product Development

by

Harry H. Ayubi

M.S. Aeronautical Science; Embry-Riddle Aeronautical University, 2001
B.S. Aerospace Engineering; Arizona State University, 1987

Submitted to the System Design and Management Program
in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

at the

Massachusetts Institute of Technology

June 2011

Signature of Author ________________________
Harry H. Ayubi
System Design and Management Program
May 2011

Certified by ________________________
Thomas Allen
Thesis Supervisor
Howard W. Johnson Professor of Management, Emeritus
Professor of Engineering Systems, Emeritus

Accepted by ________________________
Patrick Hale
Director
System Design and Management Program

"Let no new improvement in flying and flying equipment pass us by."

– William E. Boeing

Advanced Skills Required for Engineering Leaders in Global Product Development

by

Harry H. Ayubi

Submitted to the System Design and Management Program
On May 2, 2011 in Partial Fulfillment of the Requirements for the Degree of

Master of Science in Engineering and Management

ABSTRACT

Observations from first hand experience on the Boeing 787 Program during development of perhaps the most important and exciting new commercial airplane in recent history has identified opportunities to enhance the global product development skills of key engineering leaders. Extreme challenges related to typical factors (e.g., cost, schedule, quality) are coupled with a radically different business model – one shaped by a product development strategy that relies heavily on globally dispersed risk-sharing partners. In addition, the 787 would use dramatically new carbon composite materials and manufacturing methods for the airplane structure, as well as advanced technologies for the airplane systems and propulsion. This was further complicated by the parallel development of new design software intended for use in creating, sharing, and managing all 787 product definition data.

The lead design engineer – among the most critical resource on the product development team – must engage on all fronts. Given the complexities of this endeavor, advanced skills are necessary for engineering leaders to succeed, and Boeing must ensure they have these skills. This research was intended to specify some of these advanced skills, identify deficiencies in the current workforce, and suggest ways in which industry and academia might team together to address such deficiencies.

Thesis Supervisor: Thomas Allen
Howard W. Johnson Professor of Management, Emeritus
Professor of Engineering Systems, Emeritus

***"Dream no small dream; it lacks magic.
Dream large, then make the dream real."***

– Donald W. Douglas

ACKNOWLEDGMENTS

I would like to thank Boeing for a remarkable opportunity to pursue personal and professional development through lifelong learning and continuing education. Boeing's strength and competitive advantage come from its employees. Accordingly, Boeing invests in its workforce through programs like the Learning Together Program, which facilitates advanced learning and career development opportunities for all employees. In 2006, $105 million was invested in LTP, enabling 2,375 undergraduate and graduate degrees to be completed, and funding 20,400 employees enrolled in degree programs. I was one of those employees when I began the SDM Program at MIT.

I would also like to thank the leaders who provided recommendation letters in support of my application to SDM. Pat Shanahan (LFM, '91), whom I've known since I came to Boeing in 1997, and supported on many production recovery efforts. Leslie Lauer, who provided challenging opportunities early in my career, allowing me to experience a broad spectrum of the airplane manufacturing business. And Dr. Marvin Smith, Professor of Aeronautical Sciences at ERAU, who helped me to discover academic excellence.

I must thank my management team on the Wing LCPT, who supported my (seemingly crazy) idea to pursue this demanding program while continuing my difficult assignment on the 787. Mark Jenks (LFM, '91), Larry Schneider, Mike Dickinson (LFM,'99), Courtney Makela, Tom Ritzert, and Jeff Plant.

Many thanks to Pat Hale, SDM Program Director, for believing in me when others would not, and giving me a chance to prove that we were right, and that this program was right for me. Bill Foley and Chris Bates, for patience in dealing with the delays in completing my thesis, and Helen Trimble, for her thoughtfulness and help throughout the years.

A special thanks to Tom Allen, a unique Professor who is so much more than my Thesis Supervisor. His understanding of the challenge I faced at Boeing, and his patience, wisdom, guidance, and motivation helped me get to the finish line without unnecessary sacrifices to other things equally important.

To my Dad, whom I am fortunate to have as someone to try to make proud, and who has inspired me to pursue education for as long as I can remember.

And of course my family, who sacrificed much as I devoted many evenings and weekends that were meant to be shared with them – my wonderful wife Alexa, and my brilliant and beautiful daughters Tessa and Alison.

"We want more of creating special things and creating a very special environment."

– Alan R. Mulally

PROLOGUE

It took me a very long time to complete this thesis. What should have taken only months ended up taking years. The long delay was in many ways similar to the delay experienced by Boeing in bringing the new airplane – the 787 Dreamliner – to the market. A compressed schedule, rapidly advancing assignments, an increasingly heavy workload, a challenging curriculum, and a growing family.

I had just completed my course work for the degree program, and all that remained was my thesis. Suddenly things got really hectic on the 787 Program as we focused on the countdown to First Flight. When Tom Allen and I both agreed to postpone my thesis until after we got that first airplane flying, little did we know there would be significant further delays. Before I realized it, another year had passed, and then another. The airplane finally flew on December 15, 2009, and what a glorious day that was!

"Never give up!" It's one of my favorite mottos. We never give up trying to find a way on this challenging new airplane program. Just like I never gave up trying to get into the SDM Program at MIT (which in itself took 2 years). And MIT never gave up on me, waiting for the completion of this long overdue thesis – and for that I am grateful.

BIOGRAPHICAL NOTE

I was working as a Systems Engineer on the 787 Program when I first approached MIT for admission into the SDM Program. I had transitioned to the role of Engineering Project Manager on the Wing Integration Team by the time I started SDM in 2006. I progressed to Engineering Senior Manager as I completed the course work two years later, working on various program priorities in support of First Flight, Certification and Delivery.

As I complete this thesis, and as we prepare the Boeing 787 for Entry Into Service later this year, I now work on the Forward and Aft LCPT as the Director of Supplier Management. My primary responsibility is to manage global supply chain operations for performance and efficiency, including Delivery, Quality, and Cost, on seven major end item work packages from our globally distributed internal and external Partners.

"A leader's role is to raise people's aspirations for what they can become and to release their energies so they will try to get there."

- David R. Gergen

RESEARCH METHODOLOGY

The intended research was predominantly based on data gathered directly from lead design engineers and first level managers responsible for designing the airplane, and developing the product definition data reflecting that design in the new product data management (PDM) database tool.

These engineering leaders contributed directly to this effort, and also directed a team effort to accomplish the total task within a specified budget and schedule, all per approved processes defined by others. As a project manager working directly with several of these engineering teams, my approach was to gather data based on first hand experience for use in determining whether specific skills were necessary in order for success.

Supplemental research was conducted by directly interviewing various design teams over the course of several days. Answers to specific questions were recorded, as were freely expressed thoughts delivered in response to general dialogue regarding the nature of the exploration. In addition to administration of the interviews, and participation in the dialogue, notes were taken by the author, and by Professor Tom Allen, who helped conduct the interviews. Thanks again to Tom, for his help, his guidance, and for his invaluable and thought provoking insights in this field of study.

MOTIVATION

Given the extreme challenges on this development program, it was expected that some required skills were absent. Recognizing that the new Global Business Model would likely continue to influence future development programs, the intent was to identify these advanced skills needed.

Matching these needs with advanced course work available from MIT could perhaps inform those working to develop targeted instruction materials packaged specifically to address the needs of companies like Boeing.

Out of diversity comes this remarkable unity.

– Richard Bach

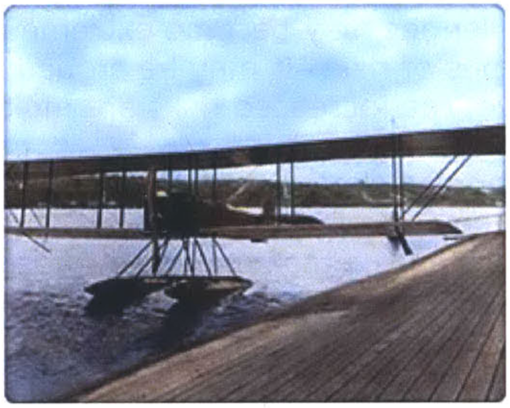
ENGINEERING AND MANAGEMENT CONTENT

Engineering content will focus primarily on the activities necessary to lead a team responsible for designing the product and developing the product definition data. In the digital design era, these two activities are differentiated. One is essentially hardware focused (i.e., the airplane structure and its systems components), while the other deals almost entirely with software systems issues. However, the same design team must accomplish both activities, and while the tasks cannot be completely separated, it is important to distinguish between the two in terms of specific steps involved during the product development cycle.

Both hardware and software product development efforts of this nature and magnitude are monumental undertakings. The potential rewards are high, but so too are the risks. When such projects have large codependence, the challenges may become extreme relative to the increased levels and types of risk. It may be argued that while the potential rewards are but additive, the increased risks are multiplicative.

Furthermore, designing the product in this case means completing the preliminary design and key interface requirements intended to drive and influence the detailed design – a task expected to be completed by others. In the past, lead design engineers knew how to do the job and knew the engineers on the team responsible to do it. With the new business model, they know none of the engineers and only part of the design job (partners were supposed to figure out all the details).

Management content will therefore focus primarily on project management challenges associated with effectively managing the activities of a small team of Boeing design engineers at home – a classic lead design engineer task – and simultaneously leading and managing the coordinated efforts of an extended partner design engineering team separated by continents and cultures.



B&W, 1st Boeing Airplane (1916)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

APU	Auxiliary Power Unit
BCA	Boeing Commercial Airplanes
BDC	Boeing Design Center (located in Moscow, Russia)
CAD	Computer Aided Design
CATIA	Computer Aided Three-dimensional Interactive Application
CCS	Common Core System
CFD	Computational Fluid Dynamics
DE	Design Engineer
DELMIA	Digital Enterprise Lean Manufacturing Interactive Application
DMS	Digital Manufacturing Simulation
ECS	Environmental Control System
EAMR	Engineering Advanced Material Request
EE	Electrical and Electronics
ENOVIA	Enterprise Innovation Interactive Application
ERAU	Embry-Riddle Aeronautical University
FHI	Fuji Heavy Industries
FLE	Fixed Leading Edge
FTE	Fixed Trailing Edge
HdH	Hawker de Havilland
H-Stab	Horizontal Stabilizer
ICM	Interface Control Model
IDG	Integrated Drive Generator
IE	Industrial Engineer
IVT	Integration Visualization Tool
JIT	Just In Time
KAL	Korean Air Lines
KHI	Kawasaki Heavy Industries

NOMENCLATURE (continued)

KVA	Kilovolt-Amps
LCF	Large Cargo Freighter
LCPT	Life Cycle Product Team
LED	Light Emitting Diode
LSSI	Large Scale Systems Integration
MHI	Mitsubishi Heavy Industries
MIT	Massachusetts Institute of Technology
MLE	Moveable Leading Edge
MS	Microsoft
MTE	Moveable Trailing Edge
MWB	Main Wing Box
NPV	Net Present Value
PDM	Product Data Management
PFW	Pfalz-Flugzeugwerke (Aerospace supplier in Germany)
PGA	Profitable Growth for All
PLM	Product Life-Cycle Management
PM	Project Manager / Project Management
QTD2	Quiet Technology Demonstrator
RAA	Responsibility, Accountability, and Authority
RPDU	Remote Power Distribution Unit
RWT	Raked Wing Tip
SDM	System Design and Management
SM	Supplier Management
SOW	Statement of Work
VFSG	Variable Frequency Starter Generator
WIPS	Wing Ice Protection System
3-D	Three-Dimensional

CHAPTER 1 – INTRODUCTION

Boeing – A Long History of Innovation

From his early days as an aviation pioneer, William Edward Boeing had a desire to improve upon existing airplanes by developing better ones. Bill Boeing came to the Pacific Northwest and settled in Washington during 1903 – the same year Orville and Wilbur Wright made aviation history at Kitty Hawk, North Carolina. A chance meeting with a young Navy lieutenant commander named George Conrad Westervelt, who shared Boeing's interest in airplanes, led to an early partnership fueled by this desire to innovate. Boeing and Westervelt had both studied engineering [1], and each had taken his first airplane ride on July 4, 1915. Boeing climbed out of the rickety Curtiss seaplane after just one flight and told Westervelt they could build a better one [1]. Soon afterward the B&W Model 1 was born.

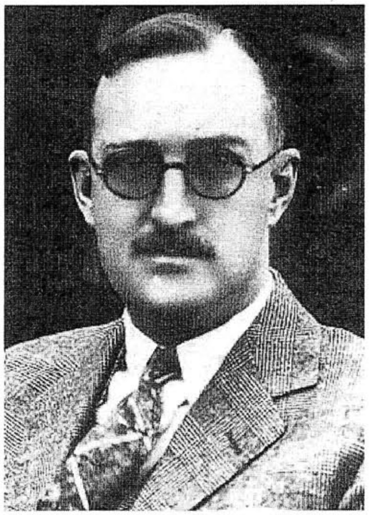


Figure 1. William Boeing [2]

Figure 2. Conrad Westervelt [3]

---

[1] The MIT aeronautical engineering program was the first in the country, started in 1914 by Jerome Hunsaker and MIT graduate Donald Douglas. Westervelt was one of the program's first students [1].

While indeed better, the B&W needed further improvements in order to compete successfully for the military contracts Boeing was eager to obtain. So when the Navy transferred Westervelt to the East Coast, fundamentally ending their partnership, Boeing hired a Chinese engineer named Wong Tsu, a graduate of the Massachusetts Institute of Technology (MIT), to advance the existing design. Wong's improved version, the Model C, eventually led to a Navy contract award for 50 airplanes, and effectively launched Boeing solidly into the aircraft manufacturing business [4].

Figure 3. Wong Tsu [5]

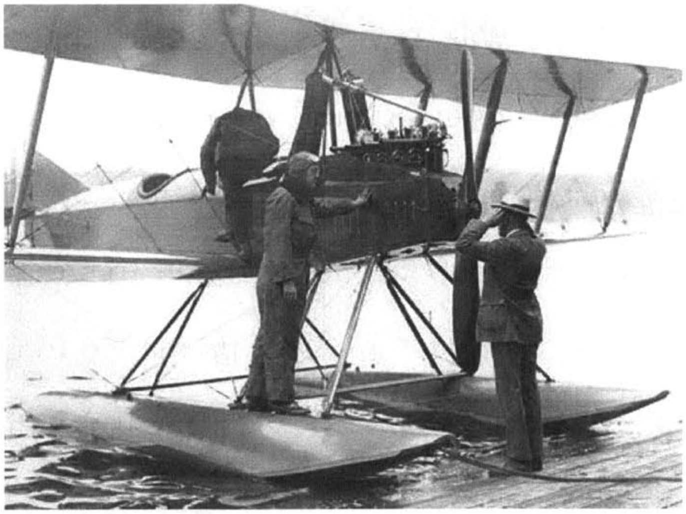


Figure 4. Boeing Model C [6]

Boeing entered the commercial transportation market a few years later with the introduction of the innovative Model 40 in 1925. Designed to carry mail for the US Post Office, Boeing's airplane proved superior to the competition as a result of Boeing's focus on continuous improvement. The Model 40 used a lighter air-cooled engine, had an increased payload up to

1,000 lb, and the ability to carry two passengers in addition to mail [7]. Less than two years later, the Boeing Model 80 took to the skies – a three-engine, 12 passenger airplane with a heated cabin, leather seats, reading lamps, and running water. This continuous focus on improved performance and passenger comfort marked the next 75 years of product development at Boeing, and is evident in the company's newest design, the 787 Dreamliner.

Douglas – Economy and Ruggedness in Design

Donald Wills Douglas was one of the most influential aircraft builders in the history of aviation. He had been fascinated with flight ever since he saw Orville Wright fly a plane in 1908 [8]. Douglas spent time at the Naval Academy in Annapolis, but then left to study engineering at MIT. After graduating from MIT in 1914, he moved to California to work in the fledgling aviation industry, and in 1920 established the Douglas Aircraft Company.

Figure 5. Donald Douglas [9]

Douglas' new company grew steady and strong as he built planes for the army and the U.S. Post Office. He had a reputation as a master aircraft builder who attracted the best talent in the country [10]. In the 1930s, Douglas introduced the DC series of transport and passenger planes, including the revolutionary DC-3. With plush accommodations for 14 on overnight flights, or seating for 28 on shorter daytime hops, the DC-3 became the first airplane that was profitable to operate just by carrying passengers [11]. Rugged and economical, the DC line sustained the Douglas Aircraft business for decades. Several aircraft companies attempted to design a "DC-3 replacement" over the next thirty years, but none could match its versatility, reliability, and economy [12]. It remained a significant contributor to air transportation well into the 1970s, and hundreds of these legendary airplanes are still in use today.[2]

Figure 6. DC-3 in service in South Africa, 2006 [12]

Figure 7. DC-3 in service in France, 1953 [12]

---

[2] December 17, 2010, marked the 75th anniversary of the DC-3's first flight, and there are still small operators with DC-3s in revenue service. The common saying among aviation buffs and pilots is that "the only replacement for a DC-3 is another DC-3." [11], [12].

When Boeing gained dominance in commercial aviation in the 1960s, Douglas lost significant market share and was forced to merge his company with St. Louis-based McDonnell Aircraft Corporation. Then, in 1997, Boeing and McDonnell-Douglas merged into what is now The Boeing Company.

Although integration of the rival aircraft manufacturers was difficult at times, eventually the new company hit its stride. Teams of premier airplane designers came together to focus on product development in the great spirit of Boeing and Douglas from their early years. The timing was right at the turn of the century when Boeing announced a new product in development that would become the 787. As told by Walt Gillette, then Vice President of 787 Airplane Development, "the 787 is the first Boeing-Douglas aircraft" [7].

The Boeing 787 – Embracing Global Product Development

There were many factors that shaped the business development strategy for Boeing in the early days of what eventually became the 787 Program. Following are several key considerations, along with brief descriptions of how each may have influenced the decisions, or affected the actions, of engineering leaders during the product development process.

777 non-recurring investment cost was too high

While the 777 has been a tremendously successful product for Boeing, continues to be preferred by airline customers, pilots, and passengers alike, and is still quite competitive in the marketplace, costs incurred by Boeing to develop the new airplane were extremely high. Designed in the early 1990s in response to airlines wanting an airplane sized between the 767 and 747 [13], Boeing bore the cost for the vast majority of the non-recurring effort required to bring the 777 to market. Many estimate that it takes years – perhaps decades – to recapture that cost, even with strong sales [14][15].

This represents risk to the company, in essence betting on strong sales and efficient production capable of meeting market demand, matched to produce revenue in sufficient quantity and soon enough to overcome the adverse affects of time on the value of the investment. The new leadership team of the Commercial Airplanes division was compelled to find a way to reduce the non-recurring cost Boeing would have to pay for the development of the 787. Thus was born the idea of "risk-sharing" Partners – those who would not only share in the build responsibility, but also share in the design responsibility, thereby providing a portion of the high non-recurring cost investment required.

Time between development programs was too long

The 787 is the first completely new Boeing airplane since the 777 was introduction in the mid 1990s. It had been about the same length of time since the 777 predecessor – the 767 was introduced in the early 1980s [13]. Fifteen years between new airplane programs was a long time, and that introduced difficulty in staffing a product development team of sufficiently skilled resources to get the job done correctly and with efficiency. Boeing intended to reduce the cycle time for introducing new airplanes into the market, and the 787 was to be the beginning of this new trend. Coupled with pressure to beat the competition to market with the new advanced airplane, this had the significant effect of compression on the development schedule. In order to meet the required milestones, "around-the-clock" design would be needed.

Global economy and international sales influence work placement

Boeing employees have known for years about the effects of the increasingly global economy, particularly those working closely with production operations. International sales of commercial airplanes, as well as other Boeing products and services, have become complex campaigns – often including agreements to place manufacturing work in the home countries of Boeing's customers. Since the 787 business model included outsourcing much of the design work as well as the build, it became clear that potential airplane sales could influence decisions about which companies would receive design contracts. Manufacturing capability and capacity would certainly continue to be among the primary selection factors, but design capability and capacity was now a very important new consideration in choosing Partners. This increased complexity introduced much uncertainty into the selection process.

Desire for stabilization of the Boeing direct workforce

Aerospace manufacturing is a very cyclical business, driven by economic impacts to both commercial and military customers. Business realities force reductions in cost to remain viable and competitive in the market during times of adjustment, and workforce reductions are a common method of cost reduction. One of the benefits of outsourced labor has been increased stability in the Boeing direct hire workforce. Placing work in the countries of airline customers to offset agreements made in sales campaigns is therefore complimentary to this stabilization strategy. In the past this has applied mostly to manufacturing workers. And while this helps dampen the effects of cyclicality on the need to manage workforce levels, labor unions don't always agree with company strategy of this nature. The threat of a strike still looms as contract termination dates approach.

Although to a lesser degree, workforce reductions affect the design community as well. Among other issues, this may have influenced Boeing's technical union, SPEEA (Society of Professional Engineering Employees in Aerospace), to strike in early 2000 [16]. The effect of the SPEEA strike proved just as damaging to operations as strikes by Boeing's manufacturing workforce union, the IAM (International Association of Machinists). Contract labor is used to supplement the Boeing direct employees needed for design and technical support. This helps dampen the cyclical effects of workforce reductions (since layoffs affect contractors before direct employees), and helps provide additional buffer in case of a SPEEA strike. However, the new risk-sharing business model introduces outsourcing of work to the design community, and uncertainty in the stability of the workforce. This adds further complexity to the issues faced by engineering leaders on the 787.

Aircraft manufacturing relies too heavily on boutique businesses

One of the boldest moves and most innovative directions in airplane development was Boeing's strategy to define a product architecture for the 787 based on materials and systems that the industries of the world were using and developing. The reason for this is that airplane manufacturing relies heavily on boutique businesses – materials and products used only in aerospace – which makes them much more expensive than those based on shared technologies used in the products of other industries. Primary examples include the use of more carbon composites (instead of aluminum) and more electric engines (instead of bleed air). In both cases, engineering leaders were required to sharpen their skills and learn the new technologies.

The 787 airframe is about 65 percent carbon composite and titanium, and only about 15 percent aluminum. This represents a dramatic departure from the 60-70 percent aluminum used on commercial airplanes for a very long time [17]. Aluminum alloys used on Boeing (and other) airplanes are unique to the aerospace industry. The construction industry, the beverage can industry, and the automotive industry all use different aluminum alloys. The aerospace industry must pay the entire research and development costs for this boutique aluminum. Meanwhile, industries of the world are working on carbon fiber. For example, bridges are being built of composite because it is strong and durable – it doesn't fail from fatigue and it doesn't corrode from salt. The automobile industry is also using more composites.

In modern jet airplanes, re-circulated air is filtered and combined with outside air prior to use for cabin air conditioning. The ambient air outside the airplane at high altitudes is extremely cold (below -35 F/-37 C), low in pressure, and significantly deprived of oxygen [18]. Consequently, the air must be compressed so that it is healthy for passengers and crew. These jet airplanes have high-bypass-ratio fan engines, and use a traditional bleed air system to "bleed" or divert air from the engines' compressors prior to combustion (see Figure 8). The bleed air, already dry and sterile, gets warm and pressurized. It is then cooled in air conditioning packs, mixed with the re-circulated air, and supplied to the cabin at the appropriate temperature.

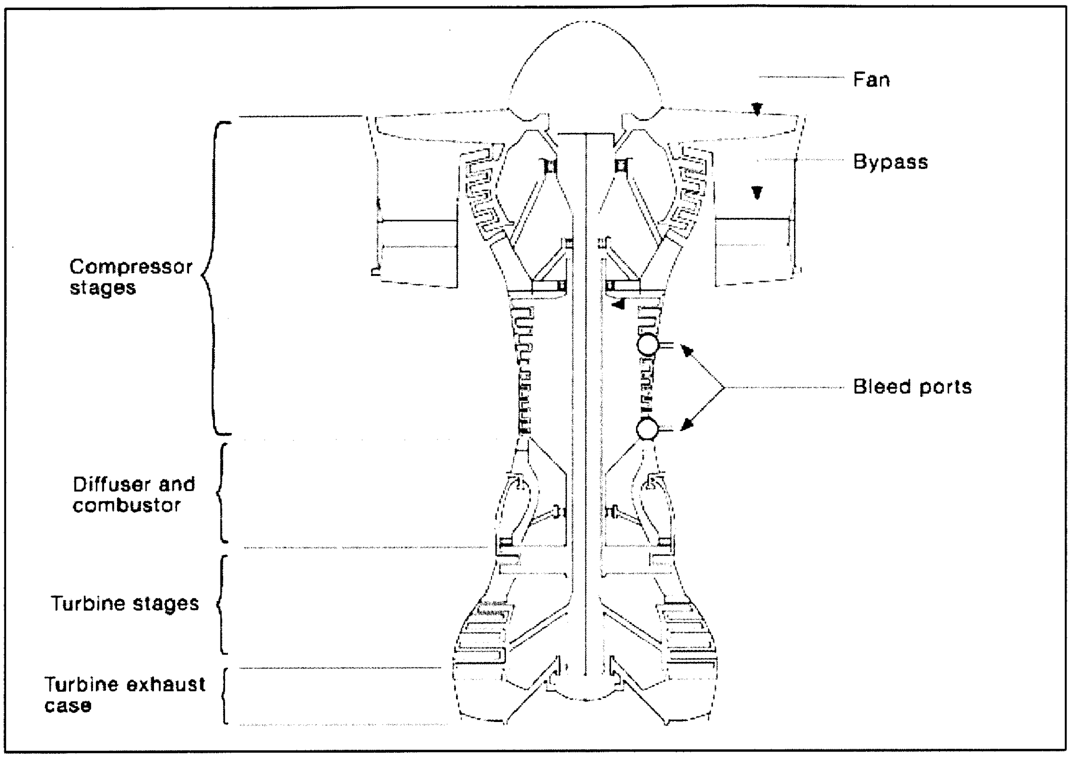


Figure 8. High-Bypass-Ratio Fan Engine (Pratt & Whitney 4000) [19]

The bleed air system is the heart of the Environmental Control System (ECS), but also provides potable water pressurization, wing and engine anti-ice protection, hydraulic reservoir pressurization, and cabin pressure [19]. The system is incredibly complex, and requires several precisely controlled pneumatically operated mechanical valves to not only supply the needs of the airplane's systems, but to discard excess heat energy when necessary.

All this has considerable adverse effects on engine efficiency. And since the bleed air is extremely hot it must be treated by large pre-coolers before it is transported along the leading edge of the wing.[3] This elaborate

---

[3] If the duct were to burst while transporting untreated bleed air, it would likely melt or otherwise cause damage to the front spar and other components along the leading edge of the wing [17].

technology is used only in the aerospace engine. Research and development costs to make bleed-air systems more reliable, more efficient, safer, and more affordable, are borne by a single industry [17]. Interestingly, it turns out that extracting shaft horsepower from these engines instead is not as detrimental to efficiency. This is primarily due to a steady increase in new technologies available resulting from the industries of the world developing new high-efficiency electric motors.

Increased environmental focus dictates taking a life-cycle approach

More so than with any previous new airplane, Boeing has taken a life-cycle approach to new product development on the 787. Life-Cycle Product Teams (LCPT) were established to ensure the focus would be maintained throughout the journey – from the very early phases of development, (e.g., concept selection, trade studies, requirements management), through the mainstream efforts of design, build, test, and deliver, and on to the longer-term stages after the product is sold, including service and maintenance.

With increasing awareness of an airline's total operating expense, design teams were able to address such issues as maintenance cost by designing for serviceability and repair, as well as for performance (e.g., low weight, low aerodynamic drag) and manufacturability (e.g., fewer parts, ergonomic installations). The life-cycle approach calls for a risk benefit analysis at every stage of development. Choosing materials that are less susceptible to corrosion, while perhaps not optimal for minimizing weight or manufacturing costs, might substantially reduce total maintenance costs over the life of the product. Attention to the impact of materials on the environment is another characteristic that received increased consideration during product development. For example, some chemicals used to treat the surfaces of metal components were not used because of the risks they pose to the environment, despite short-term benefits they might have had for the design. This strategy reduces missed opportunities, since all stages of a product's life-cycle are important considerations during the design phase – up to and including the eventual decommissioning of the product.

In time, these ideas became engrained in the thoughts and design concepts of the engineers. But the leads and managers needed to ensure these parameters did not get overlooked in the heat of the battle when the schedule pressure was high. They also had to remember to train those new to the program as they came on board, since many would not have had the same experience with previous designs. And they needed to ensure the Partners understood the intent of these requirements as well, as the driving force was often a combination of U.S. and international environmental law, and therefore unfamiliar to their design teams.

CHAPTER 2 – NEW BUSINESS MODEL

Boeing Commercial Airplanes (BCA) is the world leader in commercial aviation because of its focus on airplane operators and the passengers they serve. The Boeing family of products and services delivers superior design, efficiency, and support to airline customers, and allows passengers to fly where they want to go, when they want to go. The 787 design was shaped by this point-to-point service market strategy, and the market responded. No other new airplane product in the history of aviation has matched the market success achieved by the 787 (see Figure 9).

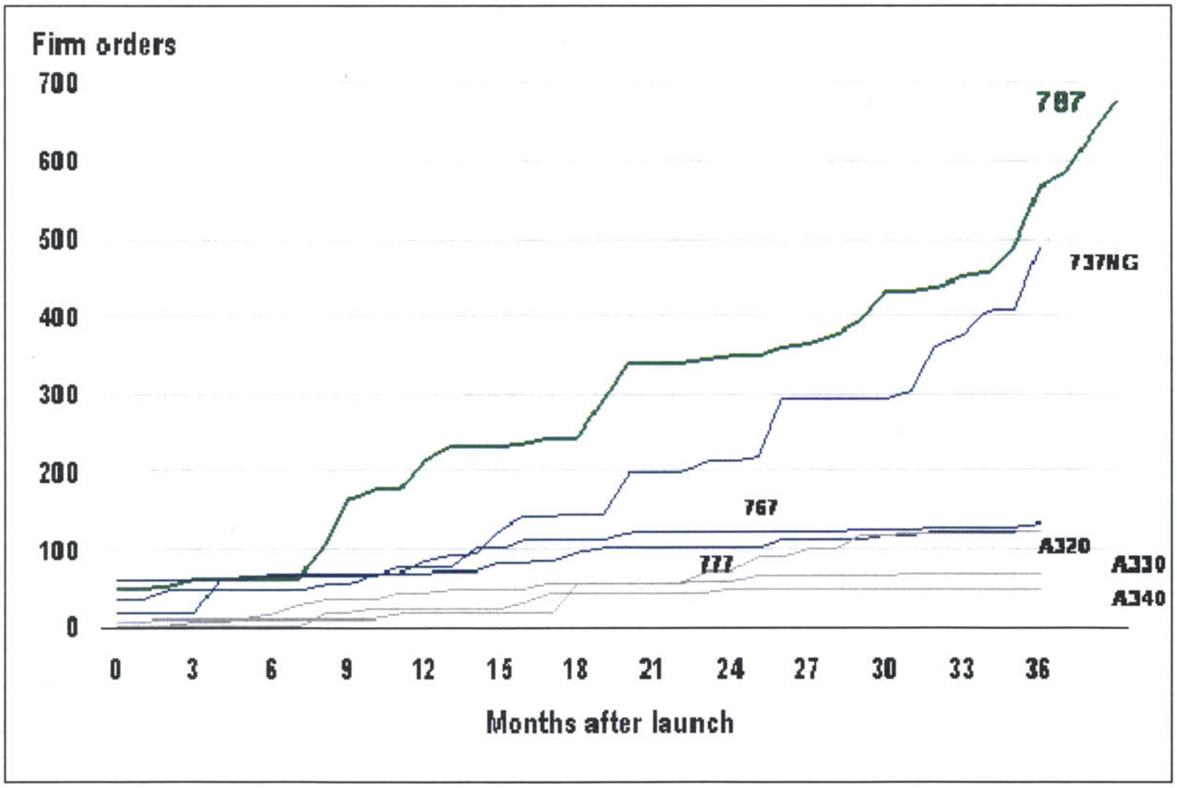


Figure 9. Airline orders for the 787 rapidly reached unprecedented levels [20].

As of late December 2010, more than 50 airline customers and leasing companies placed firm orders for over 800 new airplanes [21] (see Figure 10). The 787 is a long-range, mid-sized, twin-engine airplane designed to seat 210 to 330 passengers. It is Boeing's most fuel efficient airplane, using 20% less fuel than the similarly-sized Boeing 767. Although entry into service (EIS) has been delayed, initial deliveries are expected in 2011.

Figure 10. 54 Airline Customers have purchased over 825 787 airplanes [22].

The 787 promises a superior in-flight experience for passengers. The 787 will provide a quieter flight, larger windows, more humidity, and a cabin altitude of 6,000 feet. Compared to 8,000 feet in current aircraft, the 787 was designed to minimize muscle aches, headaches and other physical discomforts that can result from prolonged exposure to high altitude.

Intended to serve a growing global market, the 787 development effort involves large-scale collaboration with numerous suppliers around the globe performing both design and build activities. With the help of the Large Cargo Freighter (LCF), it all comes together in Everett, WA (see Figure 11).

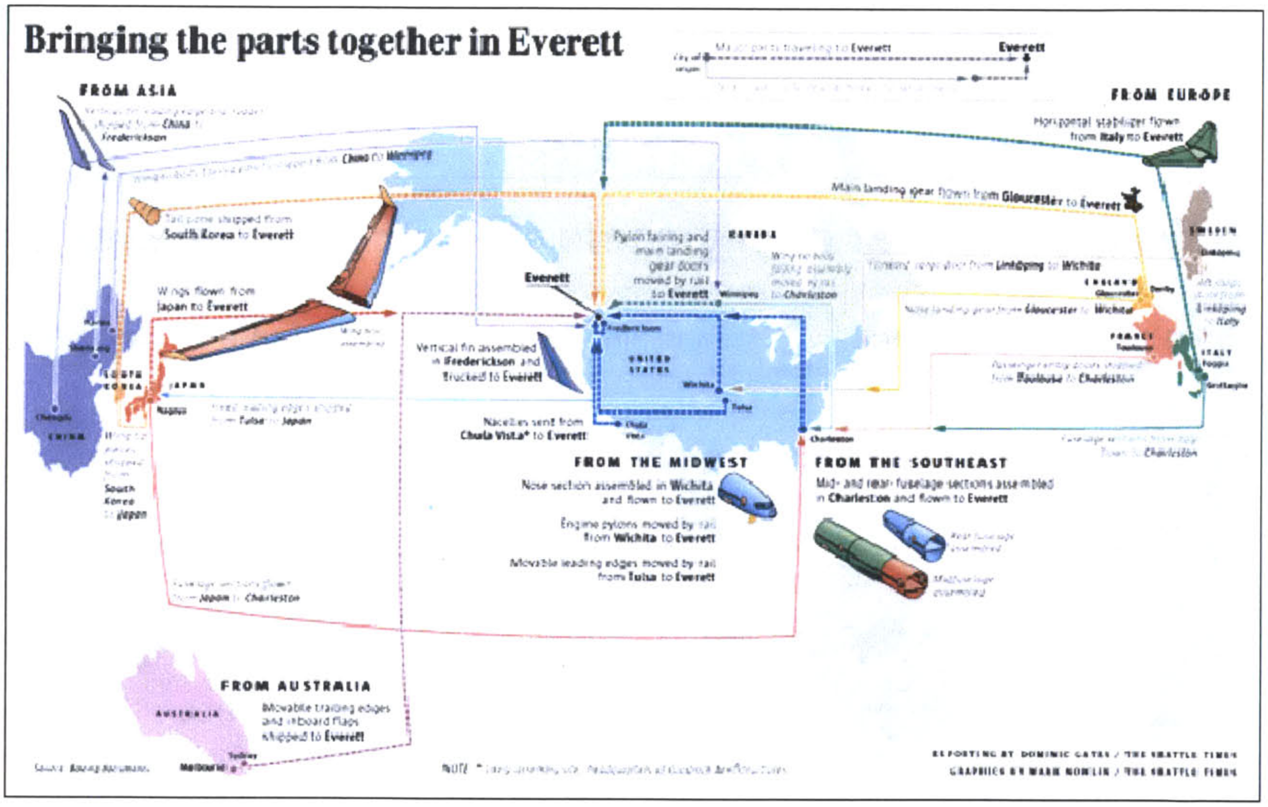
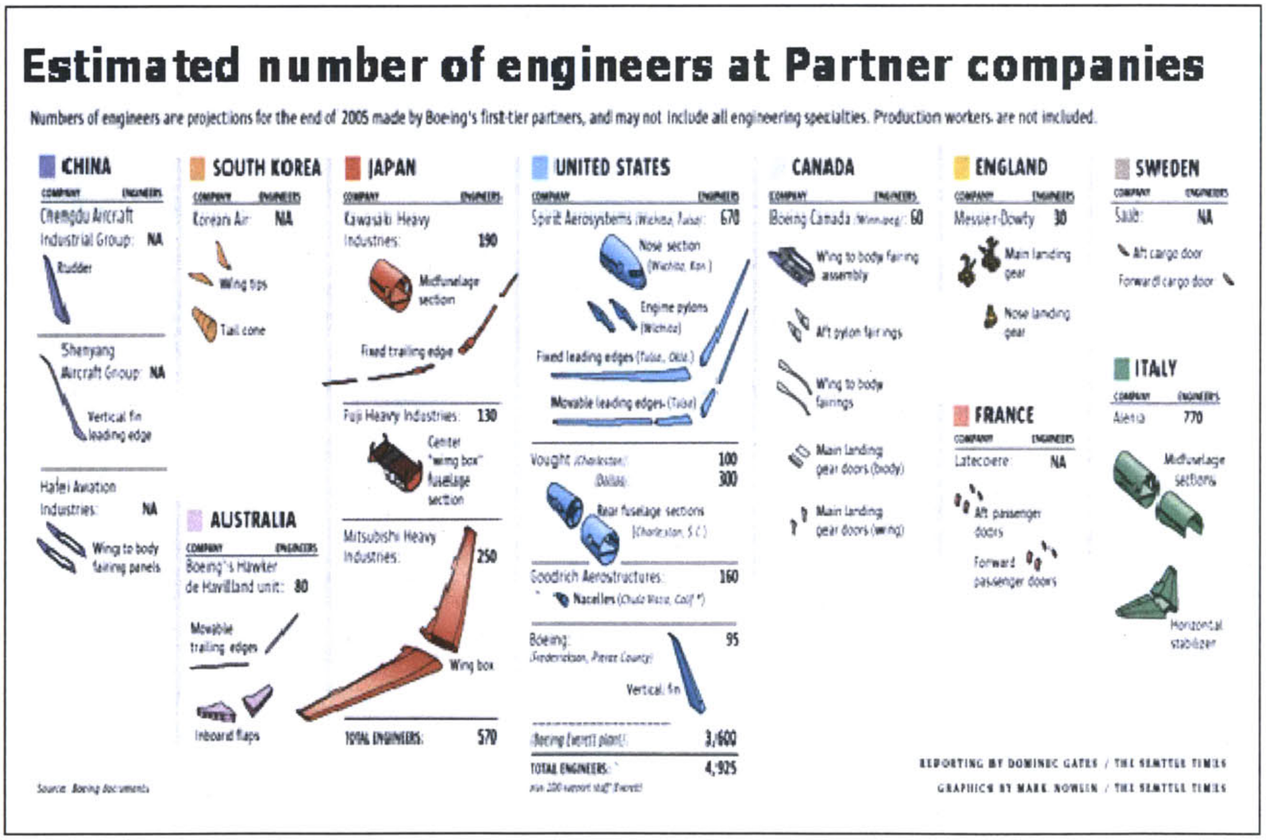


Figure 11. Globally distributed production of the Boeing 787 [23].

Globally Distributed Design

Today's innovative accomplishments result from collaboration and collective intelligence [24]. With complex products like a new airplane, the development tasks and processes can be overwhelming. Boeing addressed this challenge by expanding its team of collaborative design engineers to encompass the globe. By tapping into the vast design knowledge of Partner companies, it leveraged the intellectual capital upon which to draw from. Instead of Boeing providing all the design capability from within, the 787 captured the best design talent from seventeen different companies in ten locations around the world – each with special capabilities and experiences to contribute [23]. It was a truly global design effort (see Figure 12).


Estimated number of engineers at Partner companies

Numbers of engineers are projections for the end of 2005 made by Boeing's first-tier partners, and may not include all engineering specialties. Production workers are not included.

Source: Boeing documents

REPORTING BY DOMINIC GATES / THE SEATTLE TIMES
GRAPHICS BY MARK NOWLIN / THE SEATTLE TIMES

Figure 12. The globally distributed design team of the Boeing 787 [23].

Globally Distributed Build

The Boeing sourcing strategy for a global network of structures partners is wider than ever on the 787. Major Partners participating on the program are shown in Figure 13. As risk-sharing partners, they contribute to the high non-recurring investment required to bring the new product to market, and continue on a recurring basis to build the hundreds of airplanes sold. The fate of an airplane program is a shared destiny between Boeing and its suppliers, but this time the stakes are higher. Partner companies are betting the futures of their businesses on the success of the 787.

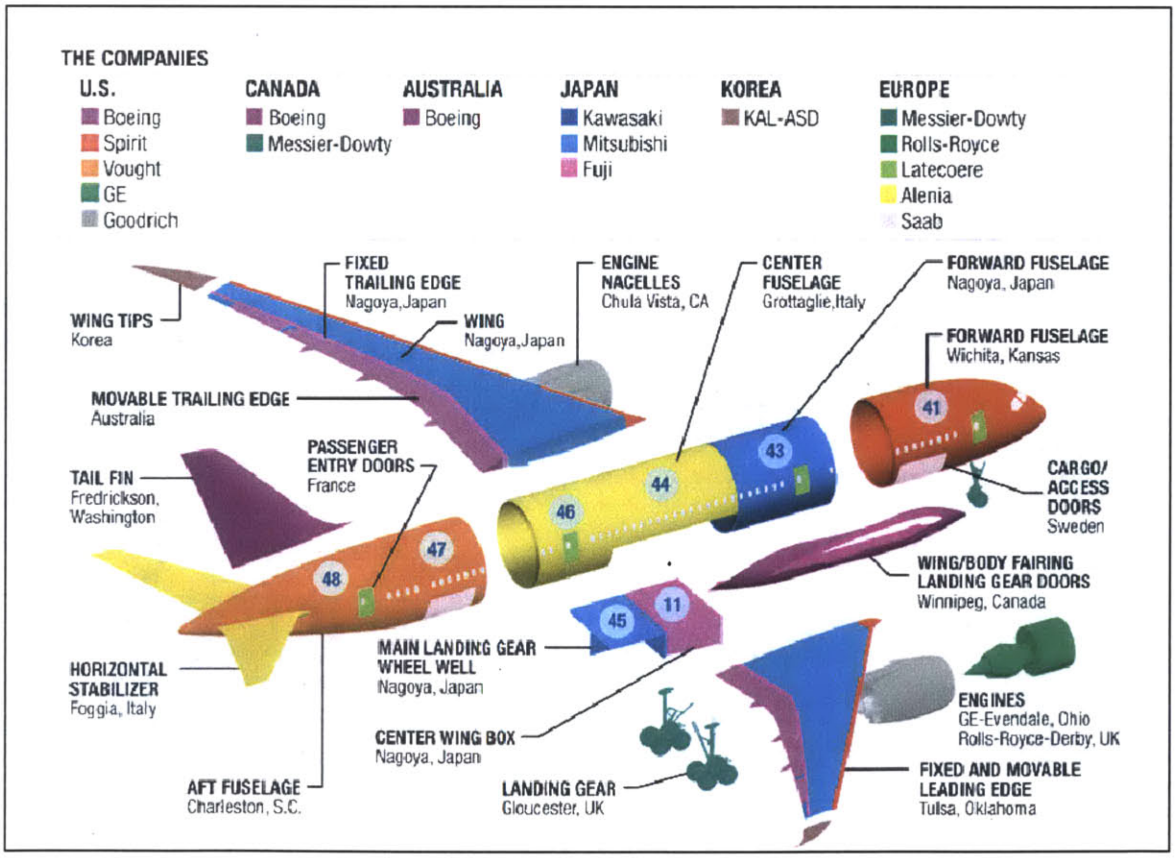


Figure 13. Risk Sharing Partners of the Boeing 787 [25].

Risk Sharing Partnerships

Systems suppliers contributing to the 787 Program are composed of top names in the industry (see Figure 14). Together with Boeing, all are focused on the same objective – to create a successful product that satisfies the customer. Most have worked together with Boeing on projects before, but all are taking on more responsibility in their contracted work packages on the 787. This enables Boeing to bring more innovation and expertise to the program, and fosters learning across companies for the benefit of the airplane and all partners. Engineering leaders must recognize and seize this opportunity in order to realize the benefits of working together.

Figure 14. Global Systems Suppliers on the Boeing 787 [26].

Large Scale Systems Integration

Large Scale Systems Integration (LSSI) is a Boeing Core Competency. In the company's vision statement, "*Vision 2016: People working together as a global enterprise for aerospace leadership*", among all the strategies, values, and core competencies listed, LSSI stands out as one that "speaks" most directly to the Boeing technical community. On the 787 Program, engineering leaders had the opportunity to put this skill into real practice.

In the broader scope of product development, LSSI at Boeing focuses on improving the efficiency and effectiveness of development programs by identifying and applying best practices, standard processes, lessons learned, common systems, and training across the enterprise [27]. Applied to the specific development of the 787, the LSSI role can take on a more tactical approach. For example, the 787 wing product structure can be decomposed into primary structural elements [28], as shown in Figure 15. In this case there are six elements (see Table 1).

Element	Abbr.	Description	Design/Build	Location	Integration	Location
1	MWB	Main Wing Box	MHI	Japan	Boeing	Everett, WA
2	FLE	Fixed Leading Edge	Spirit	Tulsa, OK	MHI	Japan
3	MLE	Moveable Leading Edge	Spirit	Tulsa, OK	Boeing	Everett, WA
4	FTE	Fixed Trailing Edge	KHI	Japan	MHI	Japan
5	MTE	Moveable Trailing Edge	HdH	Australia	Boeing	Everett, WA
6	RWT	Raked Wing Tip	KAL	Korea	Boeing	Everett, WA

Table 1. Product Structure for the Boeing 787 Wing [29].

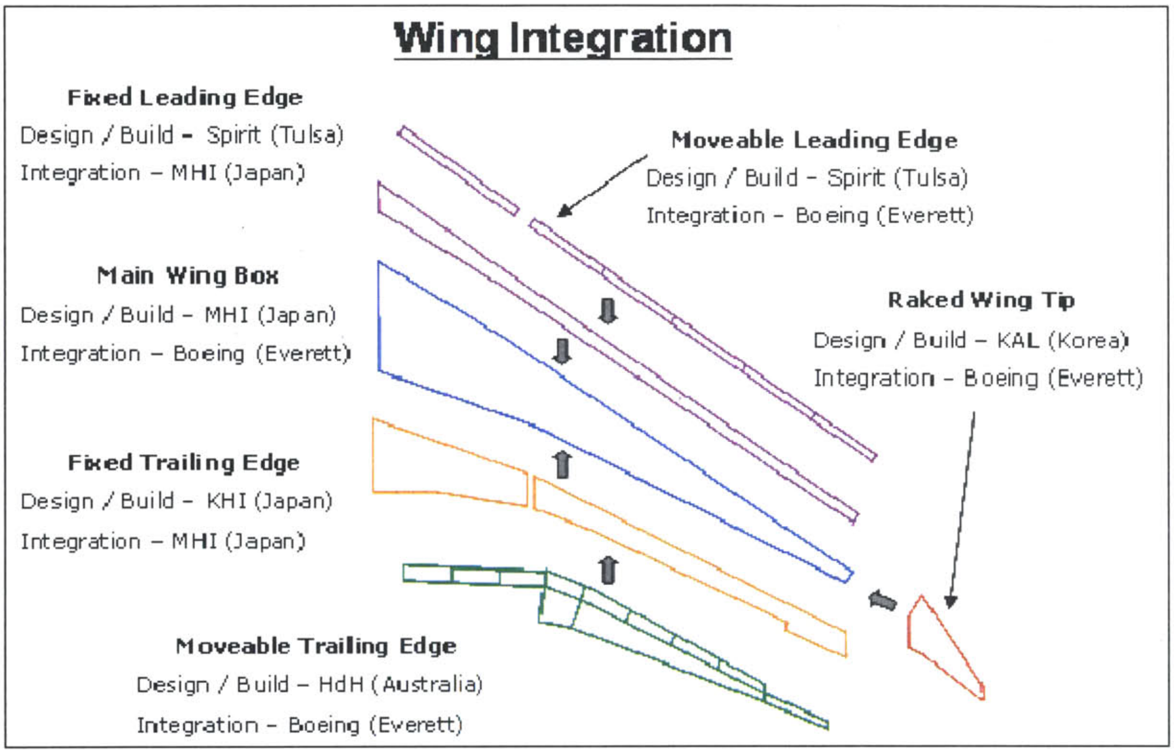


Figure 15. Integrated Product Structure of the Boeing 787 Wing [29].

Considering the wing as a "system", part of the LSSI role would include the successful integration of the system's elements – in the case of the wing, the six major structural components. For the design engineering lead, this was a primary task on the 787 development team. In some cases, this entailed extensive coordination among the design/build teams of different partners to ensure (1) that the design was well integrated, and (2) that the components could be assembled as designed. In other cases, the coordination included members for another Boeing team as well. In this role, the engineering lead functioned more like a lead integrator than a lead designer. Consider two examples to illustrate the point.

Example 1: Integration of the FLE

Primary interfaces include the MLE and MWB. The engineering lead on this team must interface with the design/build partners, MHI and Tulsa, and with the integration partners who are responsible to install the component assemblies. Since both the FLE and MLE are designed and built by Tulsa, this interface is relatively simple. One Boeing lead working with two Tulsa designers to ensure the parts work together. The FLE to MWB interface is slightly more complicated, since coordination is required among the Boeing lead, the MHI designer, and the Tulsa FLE designer. However, aside from challenges due to varying time zones, languages, and cultures, this interface is still quite manageable. But now consider the interfaces required to ensure the installations are successful. Since MHI integrates the FLE to MWB, and Boeing (Everett) integrates the MLE to MWB-FLE assembly, coordination among the manufacturing engineers from all three companies is required.

Example 2: Integration of the FTE

Primary interfaces include the MWB, MTE, and RWT. In this case, the lead has to integrate the design engineering efforts across four design/build companies – HdH, KHI, MHI, and KAL, as well as manufacturing engineering efforts across five installation companies, including Boeing (Everett). Things start to get complicated fast for the engineering lead on this work package.

CHAPTER 3: ADVANCED TECHNOLOGY

Key factors that shaped the technological development of the Boeing 787 included composite materials, advanced aerodynamics, more electric engines, and an efficient systems architecture. Packaged together, these features contributed to the expected 20 percent fuel economy improvement over similar airplanes, such as the Boeing 767 or Airbus A330 [17]. (See Appendix A for a more detailed discussion of how these factors contribute to improved fuel economy, both individually and collectively, through a process described as the "cycling effect".)

Composite Materials

The 787 is the first commercial airliner to use composite materials for the primary aircraft structure. The most commonly recognized benefit of composites and other lightweight materials is that they contribute to the use of less fuel, clearly an important consideration when trying to reduce airline operating expenses. Other benefits include less susceptibility to corrosion, reduced fatigue [4], and improved passenger comfort compared with current jetliners. Reduced material corrosion translates to less frequent scheduled maintenance for the airlines, enabling airplanes to remain in service and generating revenue. Reduced fatigue contributes to less maintenance as

---

[4] Fatigue failure life of a structural member is usually defined as the time to initiate a crack which would tend to reduce the ultimate strength of the member [30].

well, since fewer parts require replacement after years of service, but this also allows engineers to simplify structural members and make them lighter. Parts that are susceptible to failure (e.g., due to fatigue), require fail-safe designs (i.e., redundant load carrying features), which adds complexity and weight to the parts, and ultimately to the airplane.

Lastly, the strength and durability of composites enable a lower equivalent cabin pressure of 6,000 ft altitude, as compared with 8,000 ft altitude on comparable airplanes, and increased humidity. As a result, passengers will be more comfortable during the long flights [31] [32]. Figure 16 shows the extensive use of composites on the Boeing 787.

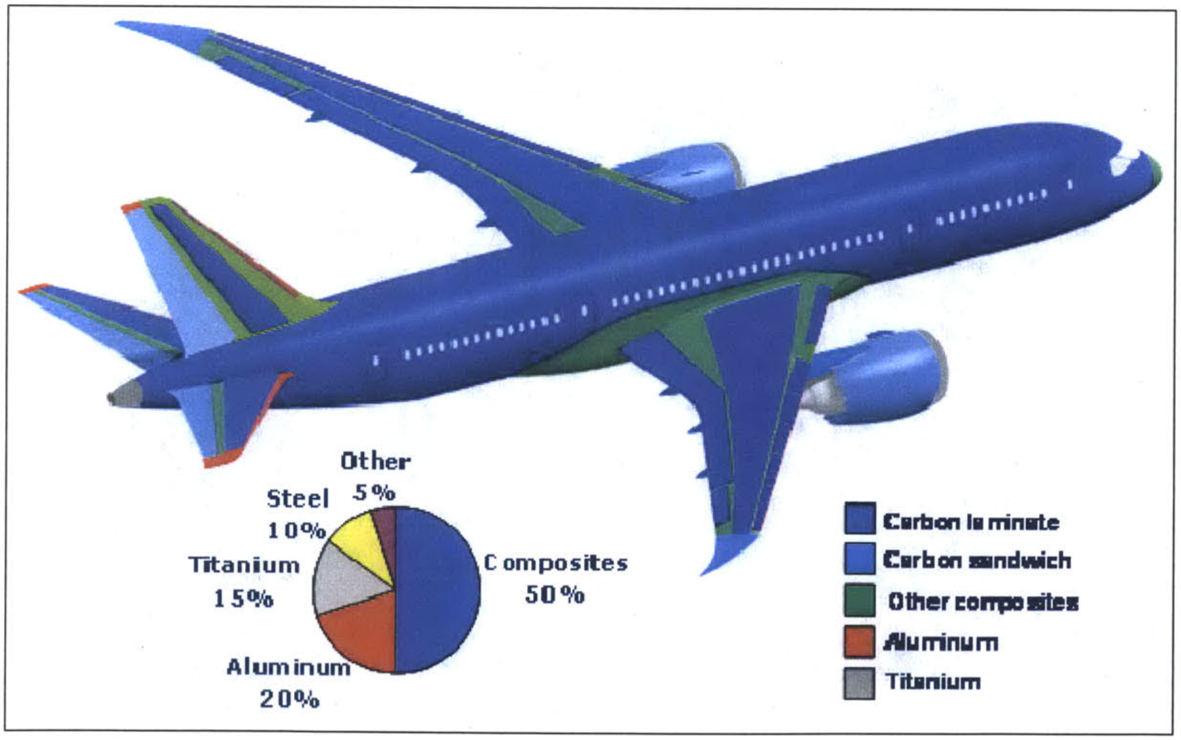


Figure 16. Advanced Materials Architecture of the Boeing 787 [26].

Advanced Aerodynamics

Based on lessons learned from existing commercial airplanes, and further enabled by the smooth finish of composite materials [33], Boeing designers use the latest in Computational Fluid Dynamics (CFD) tools to determine the airplane's shape (see Figure 17). The use of CFD design, analysis, and optimization tools is supplemented with extensive wind-tunnel testing to minimize drag and improve aerodynamic performance. The use of supercomputers enables faster set-up and run times, increased capability, and improved accuracy, all of which contribute to a shortened development schedule. The result is a more efficient airplane at a lower overall cost.

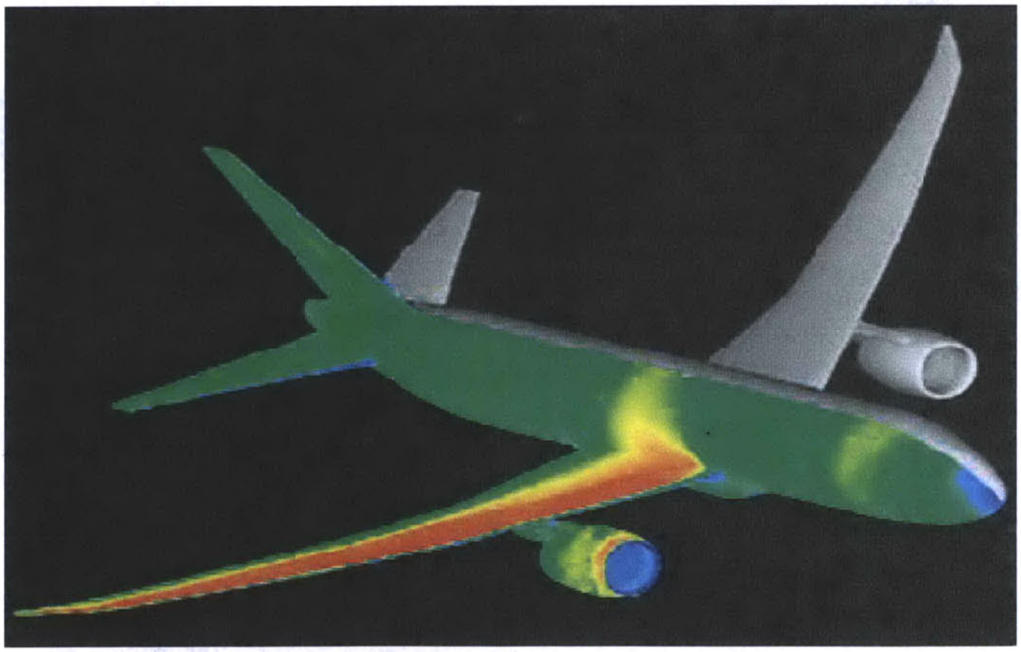


Figure 17. Computational Fluid Dynamics model of the Boeing 787 [33].

More Electric Engines

Boeing worked with engine manufacturers Rolls-Royce and General Electric to integrate the 787 Dreamliner's advanced aerodynamics with new engine technologies to improve overall airplane performance. With the shift from bleed air and associated replacement of pneumatically driven systems to more electric systems, the new engines were required to generate more electric power. Variable Frequency Starter Generators (VFSG) are used to both start the engine and function as electrical power generators after the engine starts [34]. There are a total of four VFSGs on the 787 – two on the left engine and two on the right (see Figure 18). Each VFSG generator can produce up to 250 kVA (kilovolt amps) of power. By comparison, 767 and 777 airplanes have a total of two Integrated Driven Generators (IDG), each capable of generating only 120 kVA [36]. The 787 requires a four-fold increase in power to feed the needs of its more electric systems architecture.

In addition to engine driven generators, modern commercial airplanes also have auxiliary power unit (APU) driven electrical power generators. The 787 has two APU generators (see Figure 18), each capable of producing 225 kVA [34], while the 767 and 777 airplanes have only one generator which produces 120 kVA [36]. Fortunately, today's advanced electric motors are smaller, lighter, cooler, more reliable, and require less maintenance. This has been a key enabler for Boeing in the development of the 787 engines.

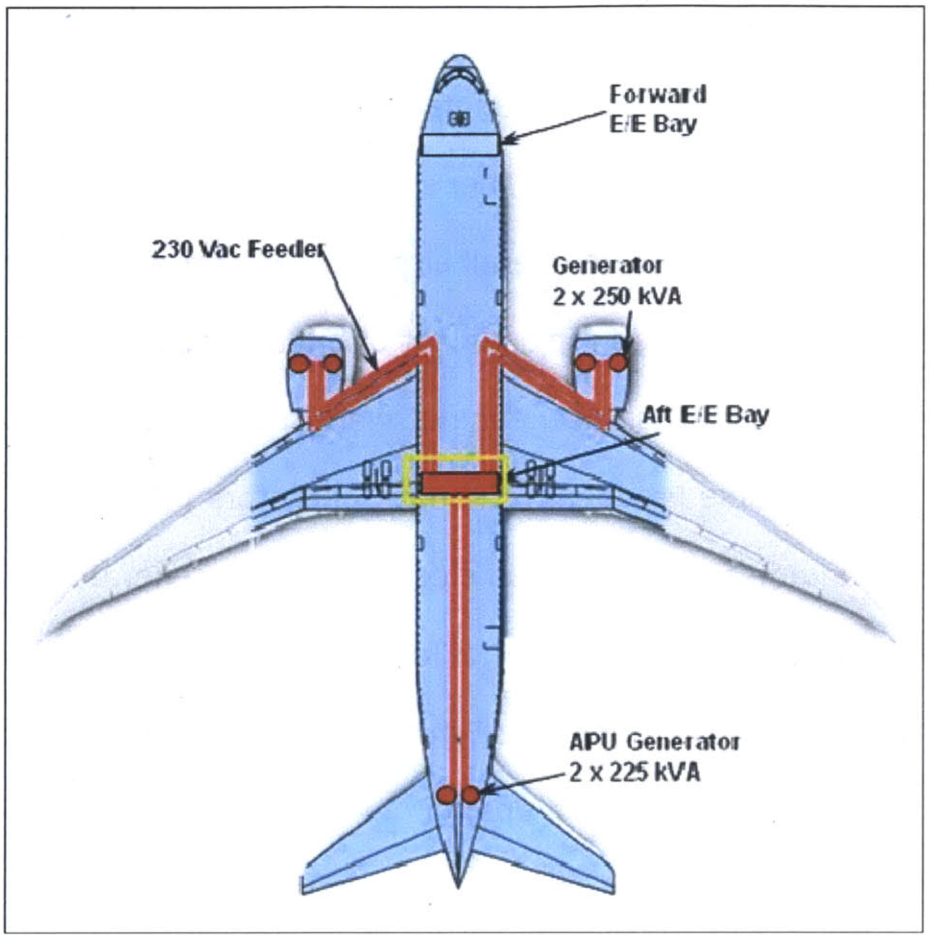


Figure 18. Electrical Power Generation on the Boeing 787 [35].

Another innovative technology incorporated onto the engines is the application of enhanced acoustics. Chevrons added to the nozzle portion of the fan cowl help reduce the noise footprint of the 787, estimated to be half that of a 767 [37]. This was demonstrated on the QTD2 (Quiet Technology Demonstrator) engine by Boeing and development partners General Electric, Goodrich, NASA, and All Nippon Airways (see Figure 19) [38]. This noise reduction measure permits the 787 to fly later at night and earlier in the morning, increasing flight operations without adding runways or terminals.

Figure 19. Boeing 787 Quiet Technology Demonstrator [38].

Efficient Systems Architecture

Changing to a more electric powered airplane was a major systems challenge for the Boeing design engineers. The team responded with an elegant architecture that was much more distributed than on any previous model. Major elements included a Common Core System (CCS), a more Open Architecture, and Advanced Power Distribution.

The CCS houses software applications and common processors that calculate data required to operate airplane functions, including the control of electrical power supply. The system uses Remote Data Concentrators (RDC) to provide system interfaces at many locations throughout the airplane [35].

Traditionally, airplane information systems have been customized for each airplane type. The 787 used an "open" systems architecture based on industry-wide standards. The increased level of commonality simplifies the integration job for the designers. It also simplifies system maintenance, upgrades, and reconfigurations for the airline operators [34].

Figure 20 shows the more efficient remote power distribution scheme of the 787 electrical system as compared with a more traditional centralized distribution. The 787 has a split EE bay, with mostly high voltage power in the aft compartment and lower voltage forward (see Figure 20). The low voltage circuits route from the forward EE bay to remote power distribution units (RPDU) for distribution, resulting in substantial reductions of wiring and associated weight [35].

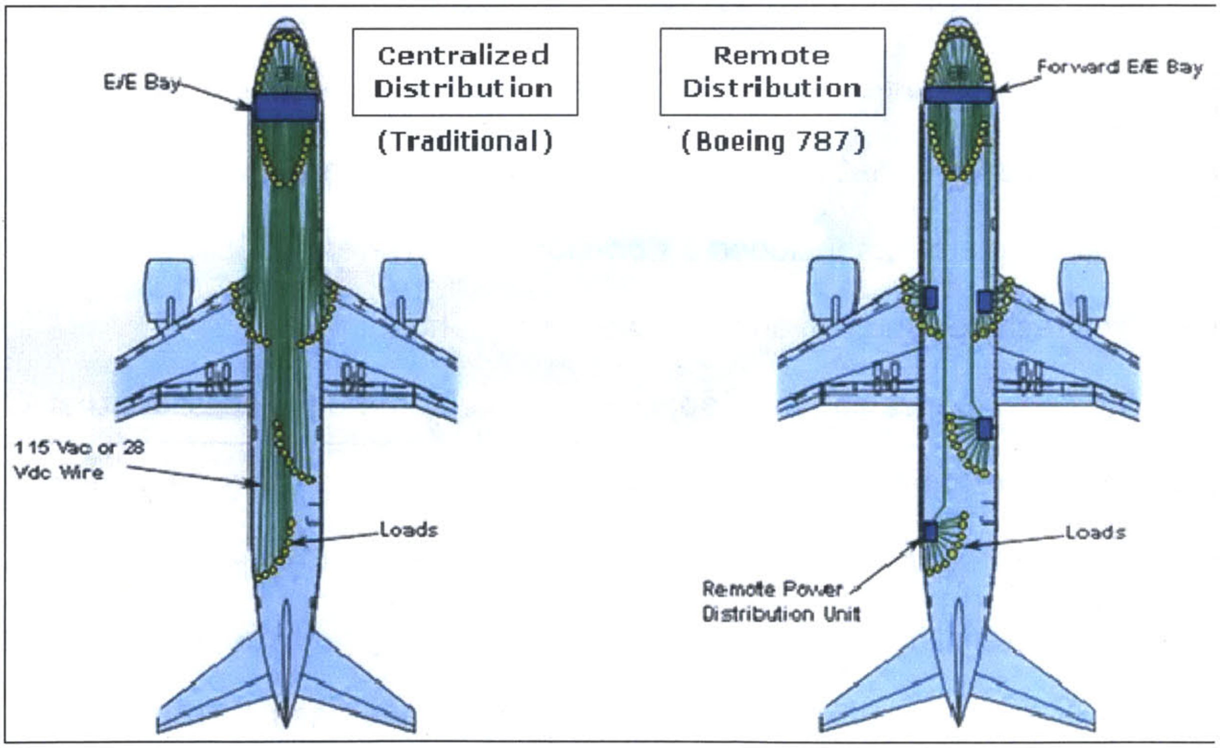


Figure 20. Remote Power Distribution on the Boeing 787 [35].

CHAPTER 4: INTEGRATED PROCESS AND TOOLS

Product Lifecycle Management

To support Boeing's efforts to design the 787 in collaboration with its global partners, it was necessary to use a Product Lifecycle Management (PLM) tool. A PLM package consists of a set of integrated software programs designed to automate and control certain processes within a business, and help manage the associated data. The software is primarily focused on the development, production, and maintenance of products. The number of modules integrated into a PLM suite varies among vendors and the industry being served, but typically there are three core programs: a CAD system for digital design; a Digital Manufacturing Simulation (DMS) system for digital assembly, which allows users to simulate how products are manufactured; and a Product Data Management (PDM) system, which manages all data associated with a product, such as drawings, specifications, and build plans.

Dassault Systems – CATIA / DELMIA / ENOVIA

Boeing anchored development of the 787 on Dassault Systems' PLM platform, based largely on the success achieved with the all-digital design of the 777 [39]. All three major components of the Dassault PLM suite were employed: the CATIA V5 CAD system for design; the DELMIA DMS system for manufacturing, which allows electronic designs created in CATIA to be used for assembly simulation, and the ENOVIA PDM system for product data management.

CATIA, short for Computer Aided Three-dimensional Interactive Application, is the anchor point of Dassault's PLM software package. Using CATIA, Boeing and Partner design engineers create detailed 3-D models of their components and run those designs through a battery of virtual tests, such as stress, vibration, noise, wind, and interface checks, long before the start of manufacturing.

DELMIA, which stands for Digital Enterprise Lean Manufacturing Interactive Application, allows manufacturing engineers to explore how parts or components designed in CATIA can be produced by simulating the build and assembly processes. DELMIA also helps Boeing and its manufacturing Partners determine how many people, robots, tools, and other resources will be required. Highly accurate and detailed simulations demonstrate whether existing assembly tooling can be utilized or new purchases will be needed, and whether processes should be automated or performed manually.

ENOVIA stands for Enterprise Innovation Interactive Application. While primarily for managing data associated with product development, it also forms a basis for collaboration [40]. Boeing uses ENOVIA to provide engineers access to 787 master data files, and share millions of engineering tasks among thousands of designers at partners around the globe.

Challenges for engineering leaders include maintaining current and accurate data for product information, ensuring that multiple design and manufacturing partners have the latest software updates, dealing with user training issues, and ensuring that rules are enforced across department and company boundaries. It was imperative that all partners using the 787 PLM suite of tools use the same software package and version of that software, and that everybody worked with the same set of product definition data [39]. (See Appendix B for a review of Airbus's PLM incompatibility issues experienced during development of the A380.)

Processes, Procedures, and Controls

Boeing established a rigorous requirement to ensure the same edition of CATIA was used by everyone designing the 787. This was necessary to ensure software compatibility. Boeing was well aware of the difficulties that could be encountered from exchanging data between different CAD systems, based on experience working with CAD packages throughout the years.

Real-time collaboration enables Boeing to quickly apply technological innovation to its products. And sharing the risk associated with development helps achieve this innovation at a reasonable cost. There are advantages to placing those closest to the manufacturing work in charge of the design. They typically know the most cost-efficient method to build the structure, by pointing out whether existing machines can manufacture a part, or if new methods and tools will be needed. By altering the design, they may be able to produce the part with existing methods faster, saving time and money. But some controls must be in place to prevent sub-optimization, and ensure the airplane can be fully and correctly integrated during final assembly.

Engineers working on the 787 were required to use CATIA V5. There were no exceptions. This was not a simple requirement, and it required a large up-front investment. Boeing and its Partners had to pay an estimated $20,000 per desktop for the software [39]. And engineers usually did not adapt well to being directed on which design tools to use [41]. Most had spent years learning to use specific software packages, often customizing them to meet preferences established through experience of exactly how their digital designs translated into actual engineering. Successful execution of this control required executive level leadership at Boeing and its Partner companies, as is usual with organizational change of this magnitude [42].

Another key component of the strategy was ensuring revision control. Even though all Boeing and Partner engineers started off with the same version of the various software packages, there was opportunity to lose control as updates were released and new Partners were brought on board. Therefore, all software updates and associated process and procedure changes took place at specified times each year – known as Block Points.

CHAPTER 5: Research Questions

Missing Information That Would Have Been Helpful

The design teams were asked to provide key insight into the specific information that was critical for success yet was missing at the time they needed it during product development. In other words, "What information, if you had it at the time, would have helped you as you learned your job?"

Project Management Skills

Recognition was slow to arrive that project management on a much larger scale would be driven down to the team leader level. The teams were not fully aware, nor perhaps was Boeing, that the design element would be a relatively small portion of the leader's responsibility, while the larger portion consisted of project management (e.g., scheduling work and establishing priorities, capturing the details of a plan from beginning to end, ensuring that the work happens, and developing status charts to measure, monitor, and report out to upper management). There was typically not a separate project manager on the team. The lead had to learn to perform the duties of a project manager, while maintaining primary responsibility for the detailed design and overall integration of their assigned work package. This required them to be good at juggling lots of things in a very dynamic environment, to make decisions with imperfect and incomplete information, and to learn to sometimes proceed with less than optimal results.

Business Skills – Contracts, Finance, and Negotiation

There was much uncertainty regarding who had primary responsibility for specific integration tasks among design partners. Issues like this must be finalized and formalized at the start of the project. Typically this is recorded in the contracts for specific work packages, along with potential remedies and financial implications for failure to perform. As the project evolves, there are numerous opportunities for negotiation based on disagreements over statement of work. Since Boeing has a technically biased work force, more business skills are needed as supplemental training.

By comparison, Partner design leaders worked hand-in-hand with their business lead counterpart, and were substantially influenced by them. Most of the Boeing design leads didn't even really know their finance counterpart. Consequently, Partner engineering teams were much more savvy about business. They had business meetings with their engineering leads, while Boeing had technical design meetings with their engineering leads.

Systems Engineering

Systems Engineering as a discipline needs to be more ingrained into the project management and daily work of the design teams. The global business model drives more dependence on a formal and rigorous process to ensure that requirements are fully developed and managed. This is expected to help the design leads address some of the more difficult issues, such as reaching agreement on statement of work responsibility, contractual obligations, and design interface management. Effective requirements management is also a potential avenue to provide influence into the design over partners with the contractual responsibility, but perhaps without sufficient expertise.

Key Lessons Learned – Value Added Experiences

The design teams were also asked to describe some of the key lessons learned during the project. In other words, "What did you learn over time that was valuable to you, and how would that have been helpful?" This section provides a summary listing of the major responses.

Cultural Awareness

Cross-cultural communication challenges are difficult to overcome, since motivations differ widely among various cultures. Therefore, robust communication plans are necessary and must be rigidly enforced. An effective communication plan should include the following elements:

- Set expectations for conduct during the meetings
- Get organized (regular schedule, contact info, etc.)
- Prioritize activities so the meetings can be efficient
- Assign actions to ensure follow-through and follow-up
- Hold rigorous reviews to make sure nothing is missed

A basic understanding of how different cultural issues may impact decisions and other behaviors of a globally diverse design team are critical to the success of the team. For example, one particular partner company based in Italy employed a work force with deeply rooted cultural behaviors such as taking an extended holiday break during the month of August, often extending up to three or four weeks long. In contrast, a two-week vacation in most American companies would be considered generous. While this can be disruptive to the synchronous efforts of a globally distributed design team, trying to change this behavior that is hundreds of years old is perhaps futile. Even if successful, the resulting effects on the partner company must also be considered. Workers giving up such a valuable and expected part of their lifestyle would demand compensation – usually monetary. The financial impact to a company already struggling to achieve a challenging business goal may in fact lead to consequences more severe than if the plan were designed to accommodate this cultural behavior in the beginning.

This example illustrates why study materials designed to help design leads perform their assigned tasks must go beyond the culture of nations. They must also address Partner company-specific culture. Engineers often need help in developing such people skills – especially when they need to deal with a broad range of diverse cultures.

Understanding the Business Model

A common understanding of the Business model, and synchronous focus by the various design team members, is essential if the product development project is to move forward efficiently. For example, the airplane weight reduction target was not in the contracts as a specific rigid requirement, so the Partners did not focus sufficient attention on this design element. However, overall cost was specified quite clearly in the contracts, so the Partners focused much of their attention on doing whatever it would take to meet the cost target. As a result, it was harder for the design teams to get the weight out of the airplane – a task commonly understood by the Boeing engineers as necessary. On the other hand, Partner engineers placed a much higher emphasis on managing the cost to design the airplane than the Boeing engineers.

Risk Management

The Partners engineers were clearly more risk averse than their Boeing engineering counterparts. This was partly cultural, and partly due to financial motivations resulting from contractual obligations. There also seemed to be a component of willingness by the Boeing engineers to take on more risk based on the expectation that, if things went awry, The Boeing Company would always be there to absorb the impact. Partners companies, depending on the size and strength of their enterprise, may not be quite as capable of weathering the storm. In many ways we all tend to align ourselves with an acceptable level of risk as determined by our culture (both nationally and at the company level). In global product development, and especially in the aerospace industry, the willingness to take risks is necessary. Often it was necessary to convey this idea to the Partners, and sometimes the message had very little effect on actual behavior.

As a result, Boeing had to take on more work in order to counteract the Partner's unwillingness to take on sufficient risk during development. And this may not change over time (at least not in the short term), since their risk level is also driven by financial effects. For example, many of the contracts are not true risk-sharing, not Profitable Growth for All (PGA), and therefore they are not incentivized to enhance performance, since they receive a fixed price amount for the work to be accomplished. It is crucial for engineering leaders to know when these motivations are in place.

As another example, changes in the configuration, due to the normal course of design progression, are viewed as changes in requirements. This drives cost assertions by the Partners, as they view this evolution of the configuration as changes to the statement of work, while Boeing engineers treat these configuration changes as standard product development tasks.

Challenges of Globally Distributed Design

The design teams were asked to describe the residual challenges that need to be addressed with the new business model, particularly with respect to distributed design teams. The following is a summary of their responses.

Large Scale Integration

The definition of Large Scale Integrator has changed. Boeing had to perform Partner-to-Partner integration, as well as the Partner-to-Boeing integration, since the Partners were reluctant to do so, citing this as Boeing responsibility. This requires Boeing to stay in the middle of all negotiations, which means more resources are needed to do the job. If Partners were to work together at a higher level of integration, then Boeing could still remain involved, but to a lesser extent. This would not only reduce redundant integration resources by Boeing, but would contribute to advanced capability development among the partners in the area of large scale integration.

Global Collaboration Tools

Global collaboration tools and processes are still evolving, mainly because of shortfalls and inefficiencies encountered during use. While this may be considered normal as a result of applying continuous improvement, it is noteworthy as design teams will constantly be required to keep up with the new technology as it evolves.

CHAPTER 6: GLOBAL PRODUCT DEVELOPMENT LEADERSHIP

Listed below are several categories of information and skills that are considered essential for success, based on the research conducted through direct interface while working with engineering leaders during development of the 787, and through face-to-face interviews of these leaders during the detailed design phase of the program.

(1) Systems Engineering
(2) Requirements Management
(3) Project Management
(4) Business Acumen
(5) 24-Hour Work Cycle
(6) Flexibility and Cultural Adaptability

Following is a brief description of these focus areas, and suggestions for how elements of each area may be applicable to enhancing the effectiveness of engineering leaders employed in the field of global product development.

Systems Engineering

Systems Engineering may be described as the management of and control over a set of product development activities. Varying degrees of formality are used, depending on the need to communicate tasks over time among the members of a project team, and the level of acceptable risk [43].

Some of the basic Systems Engineering process tasks are:

(1) Define the System (or Product) Objectives

(2) Determine the Intended Functionality

(3) Develop Performance Requirements

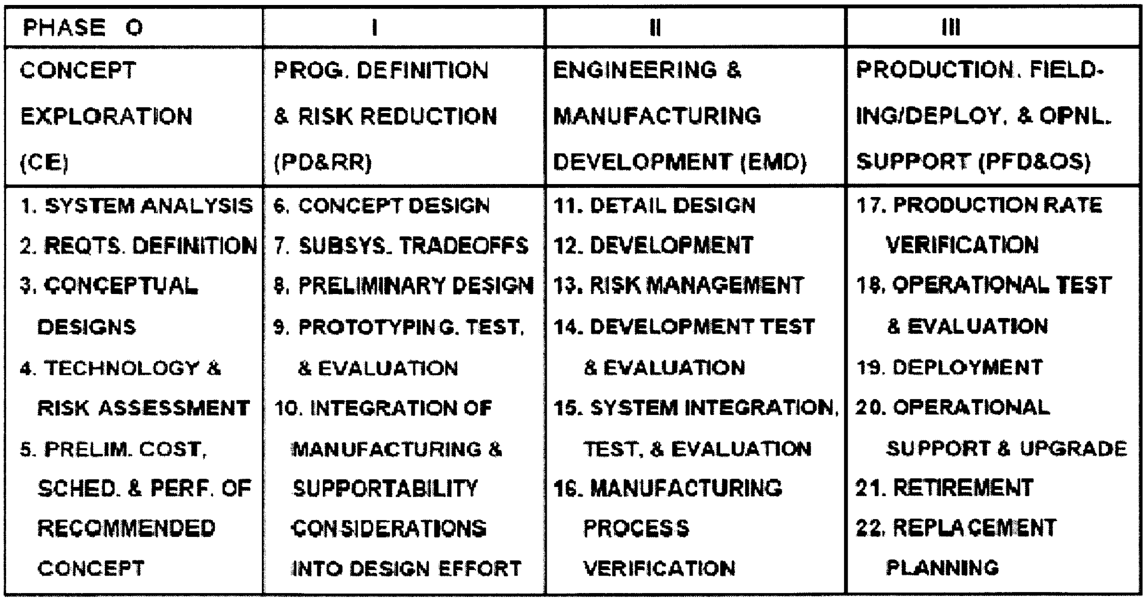
(4) Evolve the Design and Operational Concepts

(5) Establish a Baseline Design

(6) Iterate the Design Through Trade Studies

(7) Verify the Design Meets Requirements

The Systems Engineering process applies across all phases and functions conducted during a project lifecycle, as is shown in Table 2.



PHASE O	I	II	III
CONCEPT EXPLORATION (CE)	PROG. DEFINITION & RISK REDUCTION (PD&RR)	ENGINEERING & MANUFACTURING DEVELOPMENT (EMD)	PRODUCTION, FIELD-ING/DEPLOY, & OPNL. SUPPORT (PFD&OS)
1. SYSTEM ANALYSIS 2. REQTS. DEFINITION 3. CONCEPTUAL DESIGNS 4. TECHNOLOGY & RISK ASSESSMENT 5. PRELIM. COST, SCHED. & PERF. OF RECOMMENDED CONCEPT	6. CONCEPT DESIGN 7. SUBSYS. TRADEOFFS 8. PRELIMINARY DESIGN 9. PROTOTYPING, TEST, & EVALUATION 10. INTEGRATION OF MANUFACTURING & SUPPORTABILITY CONSIDERATIONS INTO DESIGN EFFORT	11. DETAIL DESIGN 12. DEVELOPMENT 13. RISK MANAGEMENT 14. DEVELOPMENT TEST & EVALUATION 15. SYSTEM INTEGRATION, TEST, & EVALUATION 16. MANUFACTURING PROCESS VERIFICATION	17. PRODUCTION RATE VERIFICATION 18. OPERATIONAL TEST & EVALUATION 19. DEPLOYMENT 20. OPERATIONAL SUPPORT & UPGRADE 21. RETIREMENT 22. REPLACEMENT PLANNING

Table 2. Systems Engineering Process Across a Project Lifecycle [43].

Systems Engineering processes have evolved primarily to support the initial phases of a program – through concept development, detailed design, production, and verification. It is widely acknowledged that 80 to 90 percent of the development cost for large complex systems is determined during the first 5 to 10 percent of the development effort [28] [43] [44] [45]. Efficient and well managed processes for defining and developing new commercial airplanes and other such systems is essential to control costs and remain competitive.

Program phases for commercial airplane development generally cover a similar spectrum of activities. Figure 21 illustrates this with a sample Master Phasing Plan – a high-level guide for the development program timeline using a phased approach.

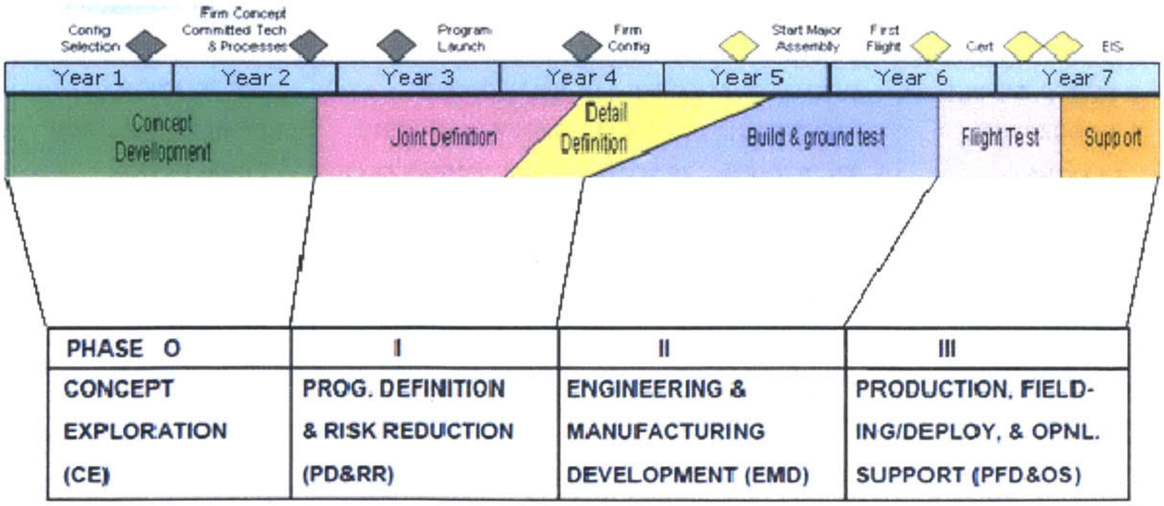
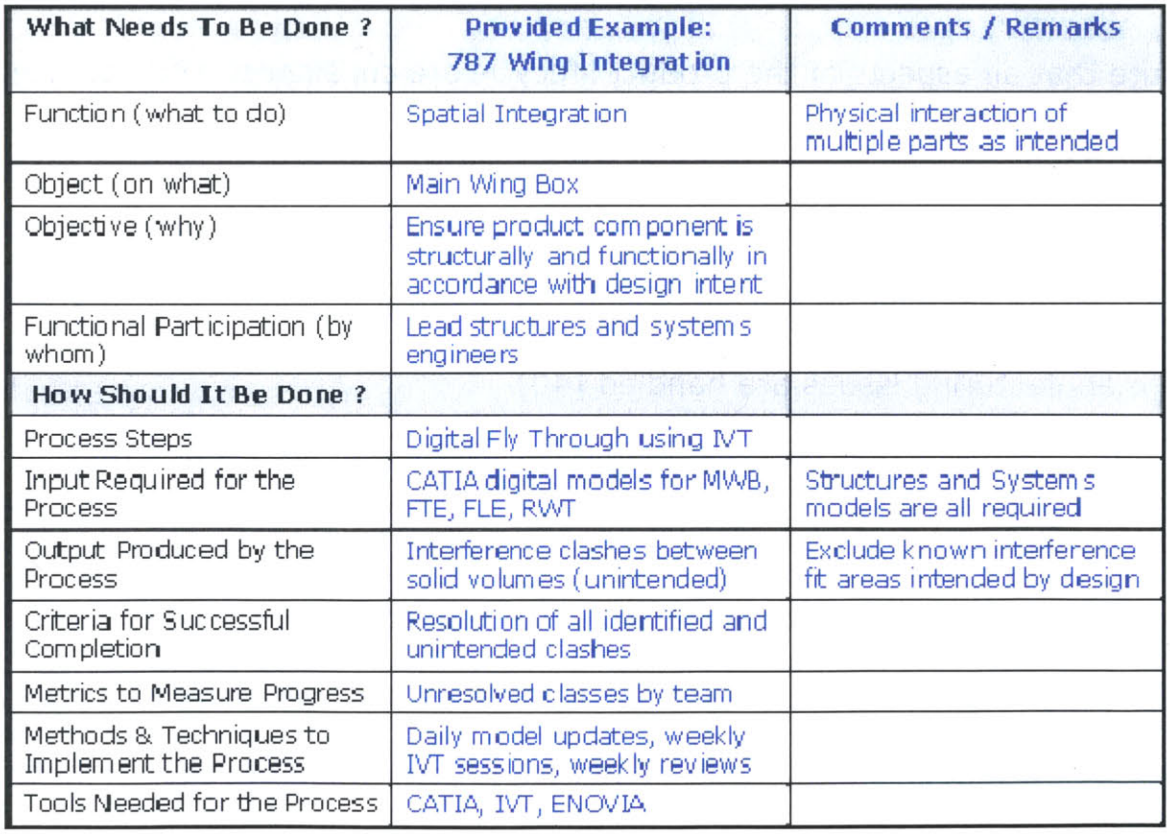


Figure 21. Master Phasing Plan for Product Development [29].

Systems Engineering is recognized as an overarching discipline, supporting tradeoffs and integration between a wide spectrum of system elements to achieve the best overall product, including many important aspects of project management. However, it is still considered more of an engineering discipline than a management discipline, and it is very quantitative, involving optimization among many engineering disciplines.

Some basic, but powerful elements of the discipline can be easily applied to the lead engineer's tasks during product development, as is shown in Table 3, including example data (blue text).



What Needs To Be Done ?	**Provided Example: 787 Wing Integration**	**Comments / Remarks**
Function (what to do)	Spatial Integration	Physical interaction of multiple parts as intended
Object (on what)	Main Wing Box	
Objective (why)	Ensure product component is structurally and functionally in accordance with design intent	
Functional Participation (by whom)	Lead structures and systems engineers	
How Should It Be Done ?		
Process Steps	Digital Fly Through using IVT	
Input Required for the Process	CATIA digital models for MWB, FTE, FLE, RWT	Structures and Systems models are all required
Output Produced by the Process	Interference clashes between solid volumes (unintended)	Exclude known interference fit areas intended by design
Criteria for Successful Completion	Resolution of all identified and unintended clashes	
Metrics to Measure Progress	Unresolved classes by team	
Methods & Techniques to Implement the Process	Daily model updates, weekly IVT sessions, weekly reviews	
Tools Needed for the Process	CATIA, IVT, ENOVIA	

Table 3. Systems Engineering Applied to 787 Wing Integration [29] [43].

A fundamental element of Systems Engineering that applies most importantly during the early phases of the product lifecycle is requirements development and management. This discipline helps to evolve the overall product architecture, and is used to balance (trade among) the competing needs of various functions and lower level system elements. It is a key area identified for skill improvement and therefore, while considered a subset of Systems Engineering, is addressed here separately.

Requirements Management

A comprehensive requirements-driven design process is necessary to ensure that all aspects of the product lifecycle are considered and balanced while an appropriate design solution is developed. For example, service, maintenance, and environmental impacts must be managed as requirements of the design solution, in the same way that more traditional performance and manufacturing issues are handled [40].

Full requirements management starts with initial efforts to define, approve, allocate, and maintain changes to requirements that are intended to influence the design of the product. This happens early in the product development cycle, and continues during detail design. A modified simple process flow model is often used to depict the application of requirements management during the development cycle (see Figure 22).

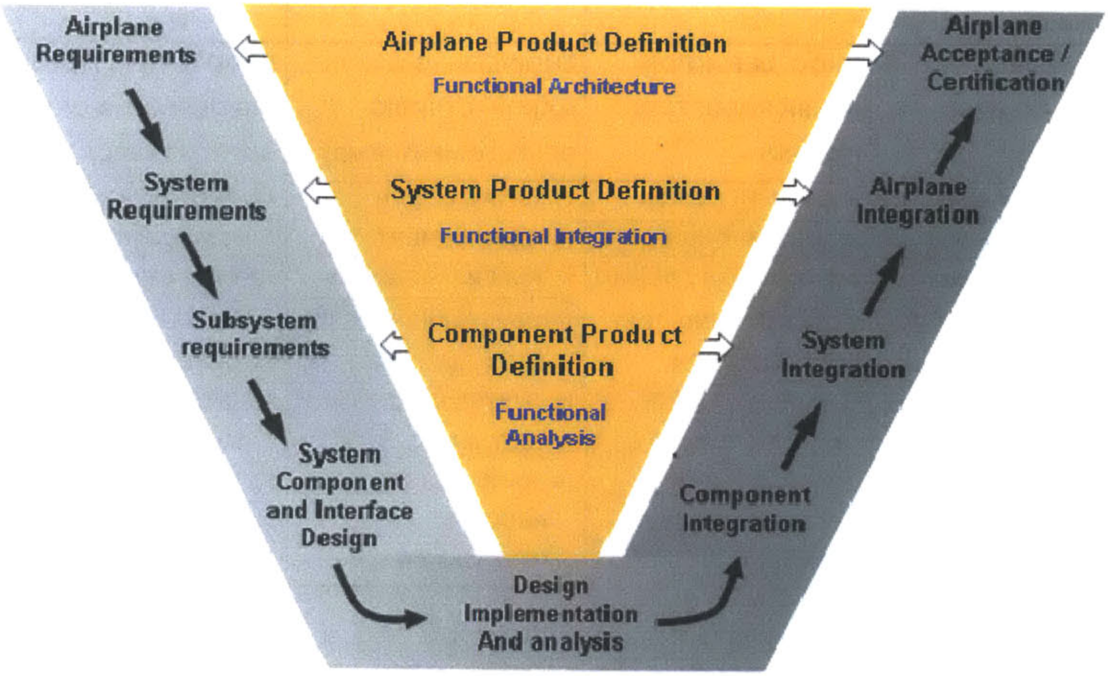
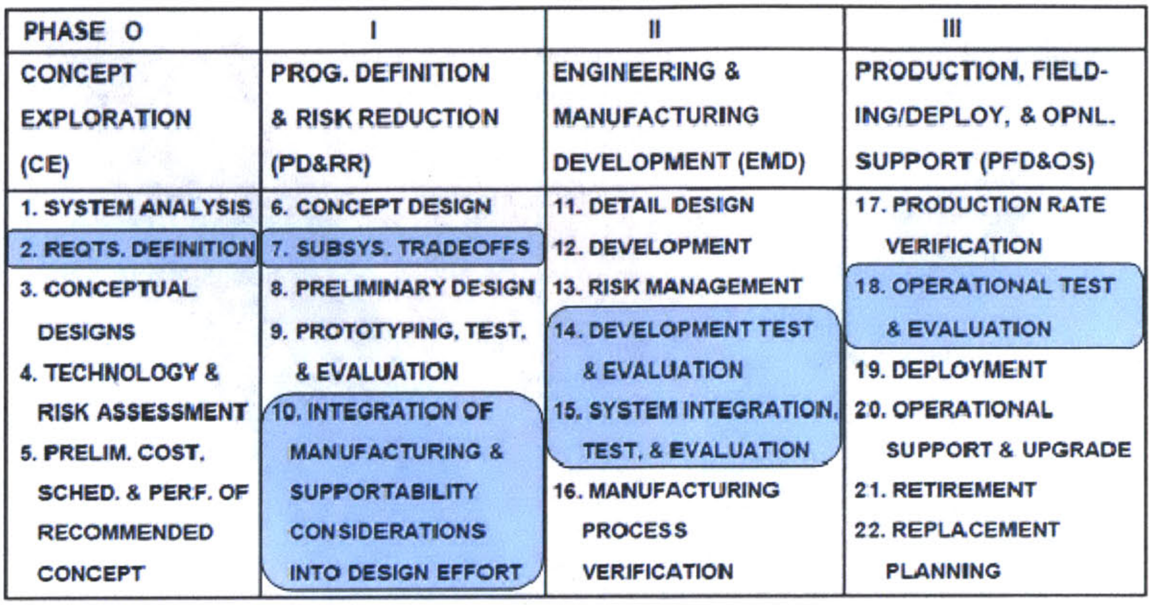


Figure 22. 787 Model for Requirements Management [29].

Ensuring that robust verification methods and practices are in place to ensure requirements are in fact met by the final design solution and build processes established is equally important, if not more.[5] Formal methods, processes, and tools are used to manage requirements verification activities. A modified table of the Systems Engineering process applied during a project lifecycle is shown below, highlighted to indicate areas of opportunity to apply the methods of requirements development and verification management (see Table 4). Engineering leaders should be well versed in these skills, and understand where they are best applied during product development.

---

[5] The requirements verification management process was an integral part of Boeing's formal plan submitted to and approved by the FAA for certification of the Boeing 787.



PHASE 0	I	II	III
CONCEPT EXPLORATION (CE)	PROG. DEFINITION & RISK REDUCTION (PD&RR)	ENGINEERING & MANUFACTURING DEVELOPMENT (EMD)	PRODUCTION, FIELDING/DEPLOY, & OPNL. SUPPORT (PFD&OS)
1. SYSTEM ANALYSIS 2. REQTS. DEFINITION 3. CONCEPTUAL DESIGNS 4. TECHNOLOGY & RISK ASSESSMENT 5. PRELIM. COST. SCHED. & PERF. OF RECOMMENDED CONCEPT	6. CONCEPT DESIGN 7. SUBSYS. TRADEOFFS 8. PRELIMINARY DESIGN 9. PROTOTYPING, TEST, & EVALUATION 10. INTEGRATION OF MANUFACTURING & SUPPORTABILITY CONSIDERATIONS INTO DESIGN EFFORT	11. DETAIL DESIGN 12. DEVELOPMENT 13. RISK MANAGEMENT 14. DEVELOPMENT TEST & EVALUATION 15. SYSTEM INTEGRATION, TEST, & EVALUATION 16. MANUFACTURING PROCESS VERIFICATION	17. PRODUCTION RATE VERIFICATION 18. OPERATIONAL TEST & EVALUATION 19. DEPLOYMENT 20. OPERATIONAL SUPPORT & UPGRADE 21. RETIREMENT 22. REPLACEMENT PLANNING

Table 4. Requirements Management Over the Product Lifecycle [43].

Proper definition goes a long way toward effective requirements management, particularly when allocating requirements to others, and especially if allocating to outside organizations that are under contract to perform development work accordingly. Some key questions for engineering leaders to consider during requirements development follow [43].[6]

(1) Is the requirement clearly stated?

(2) Is the requirement at the proper level of the product structure?

(3) Is the requirement necessary?

(4) Is the requirement consistent with applicable product standards?

(5) Is the requirement achievable and verifiable?

(6) Is the requirement traceable in the requirements hierarchy?

---

[6] This is a very brief introduction to the complex subject of requirements. See the INCOSE Systems Engineering Handbook for a more comprehensive review and systematic approach to this discipline.

Project Management

Project management can be defined as the application of knowledge, skills, tools, and techniques to a set of project activities created in order to meet requirements [46]. Successful project management is accomplished through the application and integration of specific processes, including: initiating, planning, executing, monitoring, controlling, and closing [47]. The Project Manager is the person responsible for leading the accomplishment of a project's objectives. Managing a project typically includes:

- Identifying the requirements
- Establishing clear and achievable goals
- Balancing competing demands for quality, scope/cost, and time
- Adapting plans and approach to meet stakeholder expectations

During development of the 787, responsibility for these activities was often assigned to the engineering leads and managers of each individual team. Some teams assigned dedicated Project Managers to help, depending on the complexity of the product structure they were developing, the Partners with whom they were working, or the contractual work share they were expected to perform.

Table 5 shows a typical set of tasks and how they may be distributed among the Engineering Leader and Project Manager of a team. It is clear that engineering leaders must be skilled in areas far beyond their design expertise, especially if a dedicated project manager is not on the team. In cases where the engineering leader must perform both functions, the vast majority of the leader's time and focus will be on non-design related tasks.

Engineering Leader Responsibility	Combined Responsibility	Project Manager Responsibility
Conceptual Design	Scope Control	Risk Management
Detailed Design	Schedule / Time Management	Cost Management
Design Integration	Resource Management	Procurement Activities
Requirements Development	Communication Plan	Requirements Management
Quality Assurance	Requirements Verification	Project Status
Training & Qualifications	Partner Interface	Program Interface
Design Analysis	Manufacturing Interface	Contract Negotiations
Design Reviews	Services Interface	
Development Testing	Management Interface	
Certification Deliverables	Change Management	

Table 5. Distribution of Project Management Tasks.

Business Acumen

Many engineering leads and managers conveyed a sense of urgency around the need for increased knowledge of business fundamentals. Most Partners had established design teams led by engineers that were savvy in business, and often supplemented by a business leader assigned to work with their team. This business leader would guide the design team during development activities based on an understanding of their contractual obligations, and how the terms and conditions applied to engineering tasks.

On new product development programs like the Boeing 787, work statement omissions are often discovered during the detailed design phase [48]. Work scope responsibility misunderstandings are discovered during meetings held to address these omissions and assign tasks accordingly. Disagreements are normally settled between the Boeing and Partner engineering team leaders. However, unlike the Partner teams, Boeing teams lacked sufficient business leadership skills and experience. According to one of the Boeing team leads, this placed Boeing engineering leaders at a disadvantage when negotiating with Partners on work scope responsibility and related cost issues.

24-Hour Work Cycle

The idea of a 24-hour work cycle, or "24-Hour Knowledge Factory" [7], can be traced back to the industrial revolution [49]. Tools and equipment needed to perform required tasks were scarce, and replication was costly, so workers were scheduled to perform activities in three 8-hour shifts, enabling round-the-clock use of the available manufacturing facilities. This idea can be applied to a globally distributed workforce collectively pursuing a common set of goals, enabled by modern technology and an increasingly common business language. When applied correctly, companies like Boeing enhance product development performance and improve competitiveness by reducing

---

[7] Terminology used by A. Gupta and S. Seshasai in the MIT paper titled "Toward the 24-Hour Knowledge Factory" (Paper 203, January 2004) [49].

the time required to innovate and deliver new products to market. Ideally this results in increased financial returns for both Boeing and its Partners.

In accordance with the new global business model of the 787, Boeing developed a set of "Goals and Guidance" for the Boeing workforce during the development phase of the program. This was ultimately intended to create a high performance global team with a common set of focused objectives – a key enabler to perform the role of a large scale systems integrator. Listed below is a subset of the objectives – namely those that most influenced the resulting work schedule:

- Enable the capability to work around the world
- Understand and leverage the diversity of the team
- Develop multi-disciplined and cross cultural teams
- Align behaviors and job content with the new business model
- Develop and deploy new processes, learning solutions, and skills

In order to take full advantage of the 24-hour work cycle, the globally distributed team must create a virtual work environment in which all team members adhere to an established cadence and maintain the coordination of their efforts. Engineering leaders must protect the continuity of this global operating rhythm, and ensure all team members fully understand both the benefits, as well as the potential pitfalls. Figures 23 and 24 illustrate the 'double-edged sword' effect of this strategy.

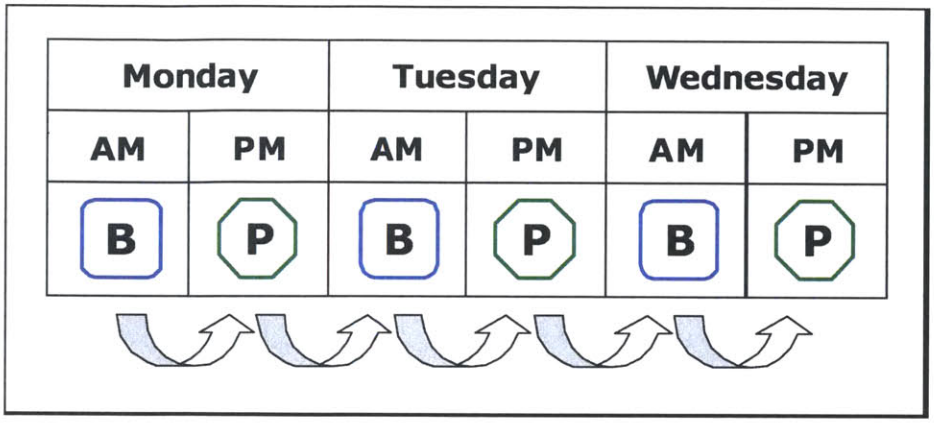


Figure 23. Global Team on the 24-Hour Work Cycle.

The blue squares in Figure 23 with letter "B" represent the Boeing team, while the green octagons with letter "P" represent a Partner team. In this simplified example, consider each team working a regularly scheduled day in their local time zone. At the end of the workday, when a Boeing team member stops working on a shared task, activity resumes by the Partner team member. Progress continues until the end of the Partner workday, upon which the shared task is again continued by the Boeing team. This cycle continues until the task is completed and another is assigned. Other team members operate in a similar manner to ensure all assigned tasks are addressed. This rhythm enables round-the-clock progress on shared tasks, and is the essential idea behind the 24-hour work cycle. While simplified in this model, the importance of the interfaces (denoted by the arrows) should not be underestimated, as they are the key determinate in success or failure of this strategy, and a major contributor to the associated cost incurred.

Figure 24 shows this same cycle and team structure, but denotes the adverse effects of a missed interface. In this case, the Partner team did not continue the shared task, and therefore lost one shift of planned progress. In many cases, however, this interruption in rhythm impacts the subsequent interface, and effectively results in a second 'miss' by the Boeing team the next day. This is because the teams tend to segregate tasks within activities that are best suited to the distinct strengths and skills of each team. When well coordinated, this strategy can double the effective output of a team, but one mistake can similarly result in twice the effective delay in progress.

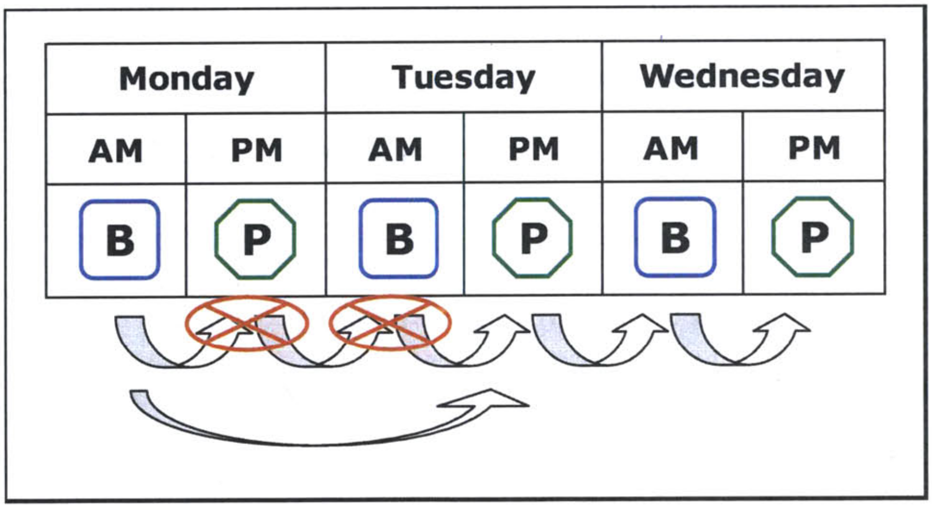


Figure 24. Effects of a Missed Interface on the 24-Hour Work Cycle.

Clearly engineering leaders must be vigilant when operating a 24-hour work cycle. They must set up and manage an effective operating rhythm that maintains the coordinated efforts of a global team, capitalizing on the increased productivity while preventing potential significant delays.

Flexibility and Cultural Adaptability

More so than with any previous commercial airplane product, Boeing is changing the face of aviation with the new 787 Dreamliner. Across the spectrum of changes – improved operating economics due to better fuel economy and reduced down time for service; lower maintenance cost due to increased durability; improved passenger comfort due to lower cabin altitude and higher humidity; enhanced flying experience due to larger, electronically dimmable windows, spacious stowbins, and LED lighting; fewer unplanned delays due to improved electronic maintenance interface; ... and on and on – the new airplane promises to be a real game changer for airline customers.

Likewise, there is a broad spectrum of changes applied to the product development process, and with those a number of new considerations for the engineering leaders that anchor the product development team. Most of these require significant flexibility and adaptability by the design team in the application of their skills, and the willingness to embrace a broadening new set of cultures to consider in the definition and execution of their plans. In addition to the challenges already described, the following list provides a sample of new considerations for engineering leaders.

The Final Assembly strategy for the future is to "replicate anywhere"

Among the most challenging requirements for the engineering team, along with the ones related to new materials and technologies, were those intended to protect a production strategy to enable the replication of final assembly operations anywhere. This flexibility drives design tradeoffs between airplane performance and producibility. Several years into the development cycle, Boeing established a second final assembly site [8] in Charleston, South Carolina - confirming the certainty of this strategy. This move illustrates the need for engineering leaders to remain flexible in their approach to airplane design practices on future development programs.

The Dreamlifter - a better way to transport airplane parts

Transportation of major structural and systems components for large commercial airplanes to a final assembly site using ships, trains, and trucks always seemed counter intuitive. This is especially true when considering the vast network of air freight operators, and calculating inventory holding costs of airplane components floating on the world's oceans for months. But this is the way it had been done for years – it is what the engineers are used to. It has shaped their design practices, and is evident in the design of most commercial airplanes. But the Large Cargo Freighter (LCF), or 'Dreamlifter', changed everything for the 787. The LCF is a highly modified Boeing 747, structurally enlarged to carry major sections of the 787 from globally dispersed manufacturing facilities to the final assembly sites. This method of transportation also drove different requirements into the design of the

---

[8] The primary final assembly site is Everett, WA, along with the Boeing 747, 767, and 777 programs.

airplane, since the cargo compartment of the LCF is not pressurized. Engineers have to take this transportation environment into account when designing and building major end items of future airplanes.

A re-marketable product is preferred by key customers

For commercial airplanes, remarketing is big business. Many airline customers sell their used airplanes to others, and airline leasing customers sell to many different airlines. Airlines distinguish themselves from others for competitive reasons, and therefore airplanes selling on the open market almost always require modifications. Sometimes these are relatively simple, but other times significant changes are required, such as replacing engines or interior configurations. The 787 was designed with requirements for easy and low cost modifications, relative to comparable existing airplanes. This re-marketable aspect has been well received by airline customers, and is expected to shape future airplane development programs. Engineering leaders have to account for the additional set of requirements in their design practices in order to achieve this highly desirable characteristic in the final result of the commercial airplane product.

CHAPTER 7: CONCLUSION

The dynamic landscape and rapid pace of global innovation is highly influenced by several major factors [50]. Those most significant to the commercial airplane product development process are listed below:

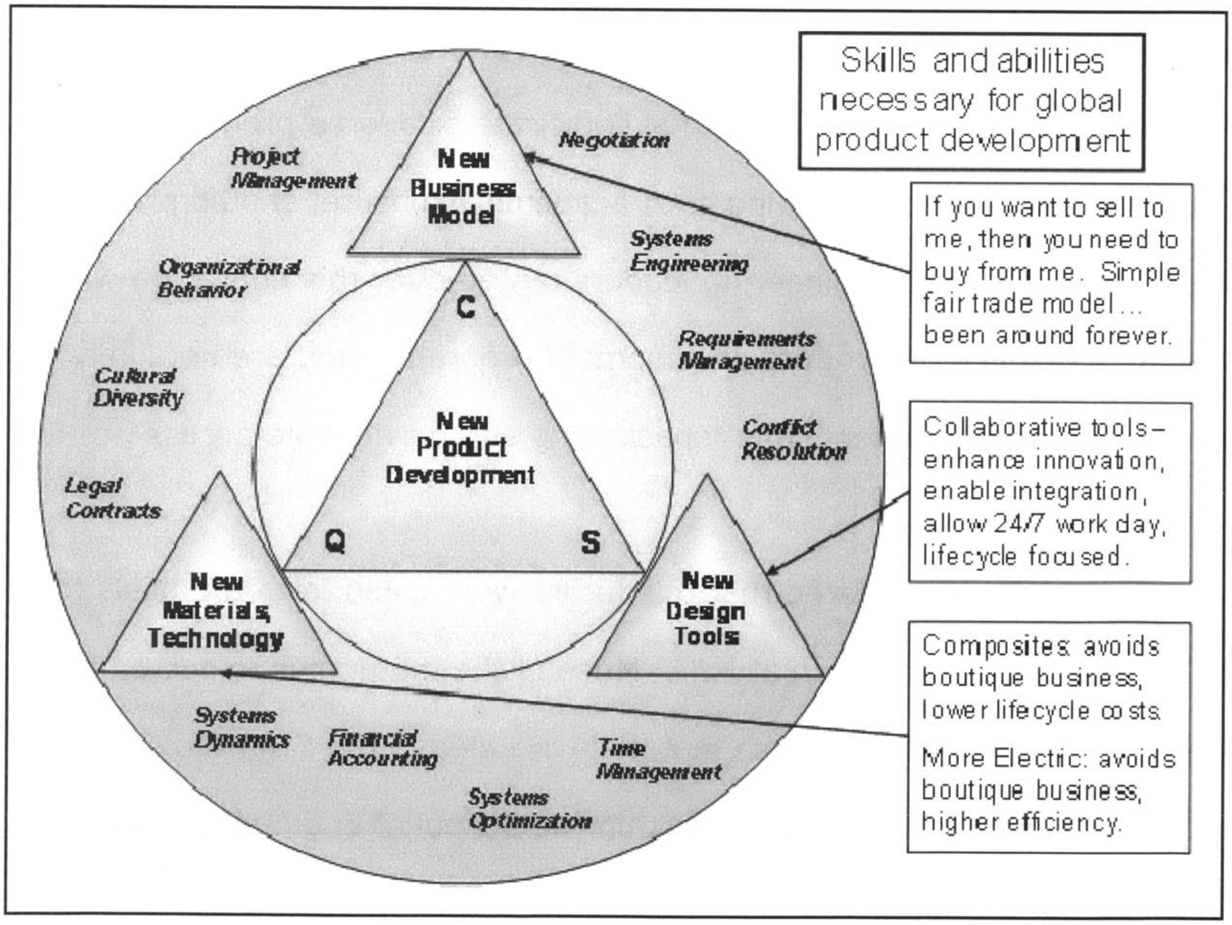
- Increasing global competition
- Increasing advances in technologies
- Changing and diverse market needs
- Increasing environmental concerns
- Evolving global technical capabilities

Boeing has clearly embraced these factors in the new global business model applied to development of the 787, establishing risk-sharing Partners for both design and production of the new airplane. The potential rewards are great, and so too are the many challenges faced by the development teams – most notably the engineering leaders who anchor these teams. Key areas identified as opportunities for advanced skills development include: Flexibility and Cultural Adaptability; 24-Hour Work Cycle; Business Acumen; Project Management; Requirements Management; and Systems Engineering.

Each of these disciplines offers specific aspects that may be expected to enhance the abilities of the engineering workforce performing product design work during the development cycle. The task remains to identify or develop academic materials that can deliver this content.

Global Leadership Skills Model

There are several elements of what may be considered success criteria for materials used to identify or develop academic course work intended to address these advanced needs. Figure 25 represents a leadership skills model that captures these elements and others in a framework for product development. Classic constraints of project management – quality, cost, and schedule – are coupled with noted challenges of the global business model applied during development of the Boeing 787.



Skills and abilities necessary for global product development

If you want to sell to me, then you need to buy from me. Simple fair trade model... been around forever.

Collaborative tools – enhance innovation, enable integration, allow 24/7 work day, lifecycle focused.

Composites: avoids boutique business, lower lifecycle costs.

More Electric: avoids boutique business, higher efficiency.

Figure 25. Leadership Skills Model for Global Product Development.

Future Research

Further research and additional work are required to identify matching or otherwise relevant academic course work that may be delivered to engineering leaders requiring these advanced skills. In cases where that identification proves difficult, specific course materials may need to be developed. However, in most cases it is expected that subsets of existing course materials will be directly applicable, and require only a repackaging of content in order to deliver just the right amount of information and in an expeditious manner. Ideally, the course materials would be made available on a pull system, allowing engineering leaders to extract the content they need just when they need it. Formal certificate or degree programs, often considered barriers to obtaining such academic exposure, should probably be avoided. Since most engineering leaders targeted for this education will be actively employed on product development programs, and are not likely to abandon their assignment, this repackaging and barrier free access is a key consideration.

It has been suggested that this future work could form the basis for a PhD project – perhaps even at MIT. Much of the material is expected to be available within existing course materials included in the SDM Program, the LGO Program, or other programs within the School of Engineering or the Sloan School of Management.

APPENDIX A - Cycling Effect: Benefits of a New Architecture [17]

Consider a 20 percent efficiency improvement of the 787 over that of similar airplanes like the 767. New technology engines contribute about 8 percent of that improvement as compared with currently available engines. Aerodynamic improvements (using three-dimensional CFD modeling) contribute another 3 percent. The increased electric systems architecture is more efficient and lighter in weight, which enables another 3 percent benefit. And the advanced material architecture, with more composites and less aluminum, results in lower weight and saves an additional 3 percent.

That adds up to 17 percent. The remaining 3 percent comes from what is called cycling. When combining these fuel efficiency improvement contributors at the same time, and then sizing the airplane using all of them, a cycling effect happens. For example, an 8 percent more efficient engine means that the airplane requires less fuel. This in turn means that the wing has to lift less fuel, which allows the wing to be smaller. A smaller wing is lighter and has less drag, which means that the engines can be smaller. A smaller engine is lighter and burns less fuel, which means less fuel is needed in the tanks, which are located in the wing. Therefore, with less fuel, the wing gets lighter, and smaller, and has less drag. So the engine gets smaller as well, and so on. This is the cycling effect. It doesn't go on forever, but on the 787 it was worth another 3 percent.

APPENDIX B – Airbus' Incompatibility Issues with CAD [39]

The A380 was delayed by two years and estimated to cost Airbus over $6 billion in lost profits. The cause was compatibility issues with the CAD software used by engineers to design the electrical wiring. Engineers in Germany used an older version of Dassault Systems' CAD software – CATIA V4, while engineers in France used a newer version – CATIA V5.

Measurement errors occurred when CAD files were passed between the two different versions of CATIA. In the Fall of 2006, when the wire bundles arrived at the assembly plant in Toulouse, they did not fit properly from one section to another. With 300 miles of wiring and over 40,000 connectors on each airplane, the immensity of the problem was overwhelming.

The two versions of CATIA were simply incompatible. They differed in their basic treatment of drawings, and so the way the digital models were created was different. Engineers designing with V4 use a manual process to create the geometry of a model. For example, to create a hole inside an object, the system requires them to subtract a cylinder from the space to define where the hole should exist. By contrast, the designer using V5 simply defines a set of instructions that describe the location and dimensions of the hole, and the geometry is automatically created. V5 uses a higher-level and more intuitive design method, but it usually takes six months to a year for someone competent in V4 to become fully proficient in V5.

APPENDIX C

Boeing 787 Chronology

1997 Aug 1: The Boeing Company merges with McDonnell Douglas. Phil Condit continues as Boeing chairman and CEO, and Harry Stonecipher, former McDonnell Douglas CEO, becomes Boeing president and COO.

2001 Jun 19: Boeing unveils model of the Sonic Cruiser, one of the options in development by the team that was also busy working on the new 7E7.

2003 Jun 15: The 7E7 is named "Dreamliner" after nearly 500,000 votes are cast in a promotion with AOL Time Warner to name the new aircraft.

2003 Dec 16: The board of directors gives the go-ahead to begin offering the 7E7 Dreamliner for sale.

2004 Apr 26: Boeing launches the 7E7 Dreamliner program with an order for 50 airplanes from All Nippon Airways (ANA).

2005 Jan 28: Boeing gives the 7E7 Dreamliner its official model designation number of 787, following an offer by the People's Republic of China to buy 60 Boeing 787 Dreamliners.

2006 Jun 30: Boeing and partner Fuji Heavy Industries (FHI) celebrate the start of major assembly for the first 787 Dreamliner. FHI is assembling the center wing section at its new factory in Handa, Japan, near Nagoya.

2006 Aug 17: The first 747-400 Large Cargo Freighter (LCF) rolls out of the hangar at Taipei's Chiang Kai-Shek International Airport. It is the first of three specially modified jets that will be used to transport major assemblies for the all-new Boeing 787 Dreamliner.

2006 Sep 5: Boeing Chairman, President, and CEO Jim McNerney appoints Scott Carson President and CEO, Boeing Commercial Airplanes. Carson replaces Alan Mulally, who was named chief executive of Ford Motor Co.

2006 Oct 17: Boeing launches widebody VIP airplanes with seven orders for the 787 Dreamliner and 747-8 announced by Boeing Business Jets.

2006 Dec 6: The Boeing 787 Dreamliner is featured in a "virtual rollout" at the manufacturing plant in Everett, Washington.

2007 Jan 16: The 747-400 Dreamlifter delivers the first 787 Dreamliner major assemblies to Global Aeronautica in Charleston, S.C.

2007 Mar 12: Continental orders five 787-9 Dreamliners. The Houston-based airline is the first customer in America to order the 787 Dreamliner.

2007 May 21: Final assembly begins on the first 787 Dreamliner.

2007 Jul 8: The first 787 Dreamliner rolls out at a celebration attended by 15,000 people at the final assembly factory in Everett, Washington. More than 30,000 participate via two-way satellite from Japan, Italy, and locations in the United States.

2008 Jun 11: Boeing announces a finalized agreement to acquire Vought Aircraft Industries' interest in Global Aeronautica. The South Carolina fuselage sub-assembly facility for the 787 Dreamliner becomes a 50-50 joint venture between Boeing and Alenia North America.

2008 Jun 19: The Power-On milestone is completed on the first 787 Dreamliner. Power-On is a complex series of tasks and tests that bring electrical power onto the airplane and begin to exercise the use of the electrical systems.

2009 Jul 30: Boeing acquires the business and operations conducted by Vought Aircraft Industries at its South Carolina facility, where it builds key structures for the 787 Dreamliner.

2009 Oct 28: Boeing announces that the North Charleston, S.C., facility, purchased from Vought, will be the location for a second final assembly site for the 787 Dreamliner program.

2009 Nov 20: Boeing holds a groundbreaking ceremony to mark the start of construction for the second final assembly site for the 787 Dreamliner program at its Boeing Charleston facility.

2009 Dec 15: The first 787 Dreamliner makes its first flight from Paine Field in Everett, Washington, under the control of Capt. Mike Carriker and Capt. Randy Neville. Takeoff occurs at 10:27 a.m. Pacific time.

2009 Dec 22: Boeing announces the acquisition of Alenia North America's interest in Global Aeronautica of North Charleston, S.C., making Boeing the sole owner. On the same day, the second 787 makes its first flight.

APPENDIX D

Boeing 787 Customers and Orders

Country	Customer	EIS	Total
Russia	Aeroflot		26
Mexico	Aeroméxico	2011	2
Germany	Air Berlin		15
Canada	Air Canada	2013	37
People's Republic of China	Air China	2015	15
Spain	Air Europa		8
India	Air India	2011	27
New Zealand	Air New Zealand		8
Papua New Guinea	Air Niugini		1
Fiji	Air Pacific		8
Kuwait	ALAFCO		14
Japan	All Nippon Airways	2011	55
Nigeria	Arik Air		7
Colombia	Avianca		12
United States	Aviation Capital Group		5
Azerbaijan	Azerbaijan Airlines		2
Bangladesh	Biman Bangladesh Airlines		4
United Kingdom	British Airways		24
United States	BBJ		7
United States	CIT Group		10
People's Republic of China	China Eastern Airlines		15
People's Republic of China	China Southern Airlines		10
United States	Continental Airlines	2011	25
United States	Delta Air Lines	2020	18
Ethiopia	Ethiopian Airlines		10
United Arab Emirates	Etihad Airways		35
Bahrain	Gulf Air		24
China	Hainan Airlines		8
Iceland	Icelandair		4
United States	ILFC		74
Japan	Japan Airlines	2011	35
India	Jet Airways		10
Kenya	Kenya Airways		9
South Korea	Korean Air	2012	10
Chile	LAN Airlines	2011	26
United Arab Emirates	LCAL		5
Poland	LOT Polish Airlines		8

Country	Customer	EIS	Total
United Kingdom	Monarch Airlines		6
United States	Nakash		2
Switzerland	PrivatAir		2
Australia	Qantas		50
Qatar	Qatar Airways		30
Iraq	Republic of Iraq		10
Morocco	Royal Air Maroc	2011	4
Jordan	Royal Jordanian		7
Saudi Arabia	Saudi Arabian Airlines		8
People's Republic of China	Shanghai Airlines		9
Singapore	Singapore Airlines		20
Czech Republic	Travel Service		1
United Kingdom	TUI Travel PLC		13
United States	United Airlines		25
Uzbekistan	Uzbekistan Airways		2
Russia	Vietnam Airlines	2015	8
United Kingdom	Virgin Atlantic Airways		15

REFERENCES

[1] R.J. Serling. *Legend and Legacy: The Story of Boeing and Its People*. St. Martin's Press, New York, NY, 1992.

[2] William Edward Boeing. Washington State Online Encyclopedia. http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=8023

[3] George Conrad Westervelt. Online Search Engine – Boeing People. http://www.yatedo.com/p/George+Conrad+Westervelt/famous/1c7b3de9b77e019d4dc89ec92216a49f

[4] Challenge (A Boeing Engineering, Operations & Technology magazine for Boeing employees), 46-47, December 2006.

[5] E. Dumovich. The First and the Best. *Boeing Frontiers*, 12: 48-49, December 2006.

[6] Model C Trainer. Boeing History. [On-line document of Historical Boeing products]. http://www.boeing.com/history/boeing/modelc.html

[7] G. Norris, G. Thomas, M. Wagner, and C. F. Smith. *Boeing 787 Dreamliner – Flying Redefined*. Aerospace Technical Publications International, Perth, Australia, 2005.

[8] Airplane Builders – Donald Douglas. Chasing the Sun. [Online]. http://www.pbs.org/kcet/chasingthesun/innovators/ddouglas.html

[9] Donald Wills Douglas. Online Media Images of Pioneers in Aviation. www.pioneersinaviation.com/images/DOUGLAS.jpg

[10] R. Sobel. *The Entrepreneurs: Explorations Within the American Business Tradition,* Weybright & Talley, 1974, Chapter 8, Donald Douglas: The Fortunes of War

[11] DC-3 Commercial Transport. Boeing History. [On-line document of Historical Boeing products]. http://www.boeing.com/history/mdc/dc-3.htm

[12] Douglas DC-3: Design and Development / Operational History. Wikipedia. http://en.wikipedia.org/wiki/Douglas_DC-3

[13] K. Sabbagh. *Twenty-First-Century Jet: The Making and Marketing of the Boeing 777*. Simon and Schuster, New York, NY, 1996.

[14] B. Shore. Boeing 777. Global Project Strategy [Online]. http://www.globalprojectstrategy.com/lessons/sucess.php?id=3

[15] Boeing 777. Global Security [Online Newsletter]. http://www.globalsecurity.org/military/systems/aircraft/b777.htm

[16] SPEEA Union. Washington State Online Encyclopedia. http://www.historylink.org/index.cfm?DisplayPage=output.cfm&file_id=2211

[17] W. Gillette. "The Boeing 787 Dreamliner: More than an Airplane." Presentation at The 8th Boeing Technical Excellence Conference, 2005.

[18] Commercial Airplanes: Cabin Air Systems. [Online Boeing document]. http://www.boeing.com/commercial/cabinair/facts.html

[19] E.H. Hunt, D.H. Reid, D.R. Space, and F.E. Tilton. Commercial Airliner ECS: Engineering Aspects of Cabin Air Quality. [Online Boeing document]. http://www.boeing.com/commercial/cabinair/ecs.pdf

[20] M. Jenks. Leading at The Boeing Company. Presentation at the MIT Leaders for Manufacturing conference. 2007.

[21] List of Boeing 787 Orders. Wikipedia. [Online] http://en.wikipedia.org/wiki/List_of_Boeing_787_orders

[22] Boeing 787 Dreamliner Customers. [Online Boeing document]. http://www.boeing.com/newairplane/787/whos_flying/

[23] Boeing Successfully Outsourcing 787 Work Worldwide. [Online] http://www.airliners.net/aviation-forums/general_aviation/read.main/3013114/

[24] T. Allen and G. Henn. *The Organization and Architecture of Innovation: Managing the Flow of Technology*. Elsevier, Burlington, MA, 2007.

[25] D. Gates. The 787 Companies. Global Trade Controls and The Seattle Times joint article. Reproduced with permission by Boeing. 2006

[26] M. Jenks. Boeing 787 – Challenges of Complex Global Systems. Presentation at the MIT SDM Systems Thinking Conference, 2010.

[27] W. Cole. Progressive Evolution: Development Process Excellence. http://www.boeing.com/news/frontiers/archive/2007/december/ts_sf06.pdf

[28] K. Ulrich and S. Eppinger. *Product Design and Development.* McGraw-Hill/Irwin, New York, NY, 2004.

[29] H. Ayubi. Wing Integration on the Boeing 787. Coursework developed in support of the SDM Degree Program requirements at MIT, 2006.

[30] Aircraft Structural Design: Design Life Criteria - Philosophy [Online] http://adg.stanford.edu/aa241/structures/structuraldesign.html

[31] Boeing 787 Dreamliner: Interior. Wikipedia. [Online] http://en.wikipedia.org/wiki/Boeing_787

[32] The Dream of Composites. R & D, General Sciences. [Online] http://www.rdmag.com/Featured-Articles/2006/11/The-Dream-of-Composites/

[33] D. Ball. Contributions of CFD to the 787 - and Future Needs. 2008.

[34] Boeing 787 - From the Ground Up. Aero Magazine [Online] http://www.boeing.com/commercial/aeromagazine/articles/qtr_4_06/article_04_1.html

[35] 787 Dreamliner Systems eBook. Boeing Training & Flight Services.

[36] C. Tenning. Designing the Boeing 777 Electrical Power System. http://www.angelfire.com/ct3/ctenning/electrical_essays/777elecpwr/777_design.html

[37] J. Hawk. The Boeing 787 Dreamliner: More Than an Airplane. [Online]. http://www.aiaa.org/events/aners/Presentations/ANERS-Hawk.pdf

[38] B. Burnett. Boeing Team Working to Make Quiet Jetliners Quieter. http://www.boeing.com/news/frontiers/archive/2005/december/ts_sf07.html

[39] M. Duvall and D. Bartholomew. PLM: Boeing's Dream, Airbus' Nightmare. Baseline - The Project Management Center, 2007

[40] H. Ayubi. Lifecycle Approach Improves Product Development Process. Article for *Pulse*, the Technical Journal of MIT's SDM Program, 2007.

[41] D. Norman. *The Design of Everyday Things*. Basic Books, New York, NY, 1988.

[42] R. Katz. *The Human Side of Managing Technological Innovation*. Oxford University Press, New York, NY, 2004.

[43] Systems Engineering Handbook. INCOSE. Version 2.0, July 2000.

[44] M. Maier and E. Rechtin. *The Air of Systems Architecting*.CRC Press, Boca Raton, FL, 2002.

[45] D. Simchi-Levi, P. Kaminski, and E. Simchi-Levi. *Designing & Managing the Supply Chain*. McGraw-Hill, New York, NY, 2003.

[46] H. Kerzner. *Project Management: A Systems Approach to Planning, Scheduling, and Controlling*. John Wiley & Sons, Hoboken, NJ, 2003.

[47] PMBOK. A Guide to the Project Management Body of Knowledge. PMI Publications, Newtown Square, PA, 2004.

[48] K. Forsberg, H. Mooz, and H. Cotterman. *Visualizing Project Management*. John Wiley & Sons, New York, NY, 2000.

[49] A. Gupta and S. Seshasai. Toward the 24-Hour Knowledge Factory. Center for e-Business at MIT. Paper 203, January 2004. [Online] http://ebusiness.mit.edu/research/papers/203_Gupta_24Hour.pdf

[50] B. Kingsland. Thinking Big for Innovation and Growth. [Online] http://www.spectruminnovation.com/PDF/ThinkingBigForInnovationAndGrowth.pdf

[51] Boeing Model 40 Meets the 787 Dreamliner. Boeing News Media. http://boeing.mediaroom.com/index.php?s=43&item=1210

EPILOGUE

Celebrating 80 years of innovative product development at Boeing

Figure 26. The only flying 1928 Boeing Model 40 flies along side the first Boeing 787 [51].

This fully restored 1928 Boeing Model 40 flies in cloudy Washington skies over Mount Rainier along with the first Boeing 787 Dreamliner. Owned and operated by Addison Pemberton of Spokane, Washington, it is the only flying Model 40 in the world and the oldest flying Boeing aircraft of any kind.

The Model 40 was Boeing's first production commercial airplane. Its innovation and efficiency were the deciding factors in winning a lucrative air mail route in 1927. That event set Boeing on a course in aviation history unparalleled by others.

The 787 and Model 40, technological leaders of their time, represent superior innovative product development in commercial airplanes. For 80 years, Boeing has been the leader in airplane design, introducing aviation technologies that have revolutionized flight and re-defined the design of commercial airplanes to come [51].