Boeing 787 Lessons Learnt
October 2008
Acknowledgements

Felix Lutsch, EIXG – 787 Overall Aircraft Design, Weight, and Performance Analysis
Iain Morgan, EIXV – Long Range Sector Manager
Peter Brink, EIXDI – Detailed Analysis of 787 Structural Design, Manufacturing and Supplier Facilities
Matthias Heimerl, YDI – Supplier Business Intelligence
Louis Nobre and Norio Yamanouchi, Airbus Japan – Local Supplier Information
Joanne Potter, PAWT1 / TWA – Production Status & Ramp-up Issues
Overview

• Design Issues
• Weight Issues
• Engine Issues
• Certification Issues
• Production Issues
  • Travelled Work
  • Lay-up Rates
  • Ramp Up
• Schedule Issues
Design Issues - Summary

• Wing
  • Center wing box static test failure
  • Lightning strike protection
  • Wiring definition

• Fuselage
  • Lightning strike protection
  • Body join across window concept
  • Mid body section join assembly
  • Aft body join assembly (including pressure bulkhead)
  • Aft body and APU tail cone join
  • MLG doors
  • Pi-Box seat rails
  • Hybrid sine-wave floor beams
  • Single-piece frames
Design Issues - Summary

- HTP
  - Center splice
  - Additional spar
- Pylon
  - Common pylon/nacelle
- Systems
  - Power Electronics Cooling
  - Brake control software
  - Generators
- Cabin
  - Wireless IFE
  - 16g seats
- Engines
  - Fuel burn
Design Issues - Wing

Center Wing Box (Section 11)

- The center wing box failed assembly-level static testing. The Issue was attributed to an FEM calculation error and classified as minor by Boeing.
- Boeing planned to implement a temporary fix for LN1 to LN6 and a permanent solution from LN7 onwards.
- Japanese supplier sources deemed this a major issue with significant impact on production.

Outboard Wing (Section 12)

- Issues with wiring definition and design changes due to lightning strike protection.
- Engineering changes were interrupted by the center wing box issue.
- In April, Boeing announced a revised wing design incorporating significant weight savings from LN20* onwards.
- A customer presentation indicates a post-EIS increase in MTOW from 219 to 227 tonnes from LN20 onwards.
- A Boeing source dated August 2008 advertised a revised airframe supporting this weight increase. This includes strengthening of the outboard wing, the center wing box, the wing leading edges, the MLG wheel well, and the center fuselage as well as enhancing manoeuvre load alleviation.
- Delivery of LN21 in 4Q 2009 leaves a tight schedule to achieve such a redesign and its incorporation into early production.
Design Issues – Wing Fasteners / Lightning Strike

• Fastener design changed to tapered sleeve bolt type late in design to prevent ‘edge glow’ within fuel tanks (1)
• At the time, production lead-time of fasteners was ~60 weeks
• This lead to a limited availability of tailored-length fasteners
• Stacks of washers conceived as a workaround created problems with incorrect assembly (2)
• Solution infringes a BAE patent owned by Airbus

![Diagram of fastener system](image)

**FIGURE 4 - AVOIDING WASHER OVERHANGS**

1. **Diagram of fastener system**
2. **Diagram of fastener system**
Design Issues - Fuselage

Body join S41/S43 and S46/S47
- Initial concept ran the join right across the window (1)
- Concept altered after barrel mating demonstration
- Windows eliminated on LN1 (2)
- No mitigation observed, not even on later models like the 787-10 (3)
- Affected passengers may not be happy!
Overview

- Design Issues
- **Weight Issues**
- Engine Issues
- Certification Issues
- Production Issues
  - Travelled Work
  - Lay-up Rates
  - Ramp Up
- Schedule Issues
787-8 Weight Evolution Charts

787_Evol_0908_EIXUG_PR0812577_v2

787-8 Positioning Evolution

Pax | Seat count | SPP Range
---|---|---
220 | Dez 02 | Mrz 03 | Jun 03 | Dez 03 | Mrz 04 | Jun 04 | Dez 04 | Mrz 05 | Jun 05 | Dez 05 | Mrz 06 | Jun 06 | Dez 06 | Mrz 07 | Jun 07 | Dez 07 | Mrz 08 | Jun 08 | Sep 08
230 | 6000 | 6500 | 7000 | 7500 | 8000 | 8500

Range [nm]

AI LR standard changed 3cl to 2cl

787-8 Design Weights Evolution

MZFW [t] | MTOW [t]
---|---
145 | Dez 02 | Mrz 03 | Jun 03 | Dez 03 | Mrz 04 | Jun 04 | Dez 04 | Mrz 05 | Jun 05 | Dez 05 | Mrz 06 | Jun 06 | Dez 06 | Mrz 07 | Jun 07 | Dez 07 | Mrz 08 | Jun 08 | Sep 08
155 | 160 | 165

program launch

September 2005 Firm Configuration (3 month delay)

MTOW increased from 200t to 205t

Firm Configuration

September 2005 Firm Configuration (3 month delay)
787-8 Weight Evolution Charts

**787-8 AI MWE Evolution**

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<th>ADS A</th>
<th>ADS B</th>
<th>ADS C</th>
<th>ADS D</th>
<th>ADS E</th>
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<th>ADS G</th>
<th>ADS H</th>
<th>ADS J</th>
<th>ADS K</th>
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**787-8 AI ΔMWE vs ADS Rev.F (firm configuration)**

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<th>ADS E</th>
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## Weight Evolution tables

**787-8**

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## 787-9

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Weight Growth Areas

Line 1 Weight Growth Since Firm Configuration

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Σ 21050 lbs
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Σ 3921 lbs

Σ 1690 lbs

Confirmed
Boeing Source Aug 2008

1. To be committed with Pi-Box
Overview

- Design Issues
- Weight Issues
- Engine Issues
- Certification Issues
- Production Issues
  - Travelled Work
  - Lay-up Rates
  - Ramp Up
- Schedule Issues
Engine Issues

General Electric GEnx

• Achieved certification of GEnx-1B in March 2008
• Rumoured to have missed SFC target by 2-3%
• Supplemental type certificate expected in March/April 2009, coinciding with estimate by FAA source that certification flight testing may start as late as March/April and another rumour that initial flight testing might switch to GEnx engines

Rolls-Royce Trent 1000

• Achieved certification in August 2007
• Rumoured to have missed book SFC by 3-4%
• Rumoured to need a revised LPT with broader chord blades, which would entail a redesign of the turbine casing. As the casing is a long lead item, the revised engine might not be available in time for certification flight testing

• Quick engine change
  • Original concept advertised an engine could be swapped in 1 hour. While this is technically feasible, the requirement remains a question.
  • Boeing now estimates the time for an engine swap to be 3.75 days, with the ultimate objective being 6 hours for a quick engine change (QEC)
Certification Issues - Summary

- FAA Special Conditions
  - Crashworthiness (NM368 25–362–SC)
  - Tire Debris Penetration of Fuel Tank Structure (NM367 25–363–SC)
  - Composite Fuselage In-flight Fire/Flammability Resistance (NM373 25–360–SC)
  - Lithium-Ion battery Installation (NM375 25–359–SC)
  - Seats With Non-traditional, Large, Non-Metallic Panels (NM384 25–370–SC)

- Other FAA reported concerns:
  - Compressed schedule and phased approach
  - Heat dissipation through composite skins
Overview

- Design Issues
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Production Issues - Summary

• Parts Shortages
• Fastener Shortage
• Travelled Work
• Conformity and Quality Assurance Issues
• Configuration Control
• Shop Floor Control
• Late Definition
• Engineering Changes
• Production Ramp-up Issues
Production Issues – Travelled Work

- Parts shortages - Insufficient supply of frames, clips, brackets, and floor beams. Root cause are
  - NDI/QA cycle time not supporting production rate demand
  - Lack of qualified NDI/QA personnel and equipment at Tier-2 and –3 suppliers
  - Deferral of NDI testing from Tier-2 and -3 suppliers to Tier-1 partners to expedite pre-assembly
  - Further deferral of NDI and assembly work from Tier-1 to FAL to rush major assembly
  - Large number of defects detected at FAL level. Removal and replacement of defect parts incurring damage and repair
  - Repeated NDI/QA testing at FAL level due to all of the above

- Fastener shortages, primarily affecting but not limited to Mitsubishi. Root causes are
  - Late change to sleeved fastener design for lightning strike protection
  - Alcoa unable to meet demand in time
  - Unbalance in fastener inventory across supply chain
  - To tackle the parts shortages Boeing has now taken a consolidated approach to inventory management across the supply chain.
Production Issues – Travelled Work

- Documentation
  - Production records on deferred work were found to be incomplete or lost in transfer resulting in a loss of configuration control

- Assembly work was found to be completed incorrectly only after assemblies reached the FAL. Root causes are
  - Oversight not adequate for the high level of outsourcing in assembly and integration
  - Qualification of low-wage, trained-on-the-job workers that had no previous aerospace experience

- Significant amount of change engineering work
  - Inadequate supplier capabilities in design, e.g. Vought had no engineering department when selected
  - Oversight not adequate for the high level of outsourcing in detailed design
  - Weight growth and subsequent weight saving changes
  - Producibility improvements

- Late Definition
  - Boeing admitted responsibility for a shortfall in wiring shipments
  - Late specification indicated by supplier as root cause
Production Issues – LN1

• LN1 entered FAL 15th May 2007
  • Delivery to Everett rushed for ‘Potemkin’ roll-out on July 8th
  • Vought S47/S48 rear fuselage structure 16% complete, systems integration 0%
  • S41/S43 sagged out of shape in transit due incomplete frame and floor beam installation (no tolerance issues)
  • Aft body join S47/S48 could not be completed before delivery, redesign underway
  • Aft body join S48/S48 (APU cone) unknown issue, redesign underway
  • Center body joins S11/S44/S45/S46 redesign for improved producibility underway
  • Replacement of temporary fasteners hampered by lack of documentation
  • 35 part numbers still missing by July 2008
  • LN1 primary structure still not complete by end of August 2008 after 15 months in FAL
  • Completion now planned for October 6th
Production Issues – LN2

- LN2 entered FAL 15th February 2008
  - LN2 structure arrived 50% more complete than LN1
  - Spirit S41 nose section structure 95% complete
  - Center fuselage assembled by Global Aeronautica contained partial wiring, flight test equipment, ducting, systems and insulation in the forward section S43 (Kawasaki) and center wing section S11 (Fuji), but significantly less in sections S44 and S46 (Alenia)
  - Vought aft body S47/S48 structure 93%, but devoid of systems and installations on delivery*
  - MHI wings delivered with temporary fasteners and parts missing

* Corroborating source believed to be Vought internal (Design News, 1st March 2008)
  - “Ship 2 went to Seattle 2 months late from last schedule change”
  - “Several 1000 parts short and no insulation, wrong hardware, no system components, full of FOD and unworked discrepancies generated by Vought”
  - “Stringer wrinkles and delamination going undetected by Vought quality”
  - “No inventory control oversight and accountability”
  - “Inability to attract competent technicians to the facility”
  - “Novice student inspectors, no competent management organization in-house”
  - “Ships 3, 4, 5, and 6 all have more defects than the fatigue model”
Production Issues - LN3

- LN3 entered FAL 2nd May 2008
  - Structure arrived 65% more complete than LN1
  - Spirit S41 structure completion level on delivery 98%
  - Systems completion level on delivery 37%
  - Structural work on fuselage mid-section continued through August
Production Issues – LN4, LN5

• LN4 entered FAL 6th August 2008
  • Delivery delayed 5 weeks due to damage sustained in production at Global Aeronautica
    • Incorrectly installed fasteners, non-compliance by temp worker
    • Ad-hoc FAA inspection highlighted FOD issues and workers bringing in their own tools
  • Spirit S41 structure 100% complete
  • Center fuselage systems installation targeted to be 50% complete on delivery
  • Vought aft body section S47/S48 structure 98% complete, systems 87% complete, including THSA as well as potable and waste water tanks

• LN5 was to enter FAL 31st August 2008 – DELAYED
  • Center fuselage was undergoing assembly and systems integration at Global Aeronautica. Completion of the wiring approximately 30-40% with major structures fairly complete.
  • Center fuselage systems installation targeted to be 75% complete on delivery
  • Aft body section S47/S48 in the final systems installation at Vought. Due to arrive with 96% of systems installed.
  • Wing ship set delivered on 23rd August with high level of completion but still some wiring outstanding.
  • Alenia horizontal stabilizer and the first Spirit GEnx-compatible pylons delivered
Production Issues – LN6…

• LN8
  • LN8 mid fuselage to be first fully-stuffed assembly delivered by Global Aeronautica
According to Spirit, composite material lay-down rates are far below projections

- The initial goal was 100 lbs/hr with a single-head machine
- Production started at 8-9 lbs/hour
- Efficiency gradually increased to 19 lbs/hour
- The rate is expected to increase to 30 lbs per hour once a new dual-head machine on order arrives.
- The rate of 100 lbs/hour now is a mid-term goal.

- The following chart has been reproduced from a video of a Boeing lecture held by Al Miller, Boeing Director, 787 Technology Integration, at the University of Washington in November 2007
- The Boeing chart is indexed to the 1980 technology level in material lay-down rates. It can be established that a rate of 0.5 lbs per hour was achieved by manual lay-down at that timeframe.
- Matching the result with the Spirit figures as above seems to indicate that the current production rate is less than a third of the targeted initial rate and almost one order of magnitude below the forecast for recurring production.
- This will have a significant impact on tooling and facility investment in order to support the targeted ramp-up in production figures.
Demonstrated

Need for higher composite lay-down rates due to 787 is being met by industry developments

Projected

Forecast Capabilities

Multi-head Improvements

Source: AIMiller, Director, 737 Technology Integration, University of Washington Lecture, 2007 November 13th (Video Capture)
787 Material Lay-down Rates - Actual

Airbus Assumption:
1980 ~ 0.5 lbs/hour

8-9 lbs/hr

Multi-head
30 lbs/hr

19 lbs/hr

8-9 lbs/hr

„Had a lofty goal of 100 lbs/hr“
„Won’t achieve that with LN1“

Material Laydown Rate (lbs/hour)


Source: A1 Miller, Director, 737 Technology Integration, University of Washington Lecture, 2007 November 13th (Note: Capture)

Actual Rates
Source: Spirit
Production – Ramp-up Schedule

• Original objective was a fast production ramp-up to achieve a rate of 10 aircraft per month in 2010

• In April 2008, the objective of rate 10 was pushed out by 2 years to 2012, with a more gradual ramp-up in deliveries in the first two years to mitigate the risk of having to rework early aircraft

• Boeing announced that due to the delay in first flight by 14 months and the slower ramp up deliveries would be “delayed by 20 month on average”

• One airline was advised by Boeing that the production ramp-up would be patterned after what was achieved with the 777 program. This would mean that only a rate of 7 would be achieved in 2012

• In fact, Boeing guidance implies that first delivery is delayed by 16 months, from May 2008 to September 2009. Moreover, announcements by various customers indicate accumulated delays of up to 36 months (JAL) with “the average in excess of 27 months” (ILFC). This matches the 777 ramp-up scenario.

• Despite this and the additional delays incurred since April 2008, launch customer ANA announced in September 2008 that they agreed with Boeing that first delivery is to happen in August 2009.
## Production – 787 Ramp-up Schedule

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Sales success driving ever more aggressive schedule

Supplier A, B figures believed to be close to actual Boeing production plan

EIXDI estimate matching 777 ramp-up profile with further rate increase required to support current sales activities for 2020 slots

Key supplier has committed to a peak rate of 7 per month, but negotiations for a higher rate have failed.
Production – Ramp-up Preparation Status

Boeing

• Second FAL encouraged by customers, but real bottleneck is supply chain

Alenia, Hawker de Havilland

• Investing in second autoclave and further equipment to support production ramp-up.

Kawasaki

• Investing in new factory and production equipment

Spirit, Vought, Global Aeronautica

• No investment in facilities or equipment, preparing for more gradual ramp-up
• Spirit unilaterally shut down the production of CFRP fuselage barrels in January 2008. Production was slated to restart in 3Q 2008
Production – Ramp-up Preparation Status

MHI

• Committed only to rate of 7 per month, facility sized for rate 10.
• Any plan to increase to rate 10 put on hold due to differences with Boeing over financing
• MHI did have preliminary order for additional tooling which was cancelled
• No intention to invest in production beyond rate 10
• MHI working on wing shipset LN7, no problems in process reported

San Antonio

• First 20 aircraft to be refurbished and modified in San Antonio, TX
• Site is on seven year lease, what for?
Overview

- Design Issues
- Weight Issues
- Engine Issues
- Certification Issues
- Production Issues
  - Travelled Work
  - Lay-up Rates
  - Ramp Up
- Schedule Issues
Production Schedule Issues

• Pre-planned product improvement
• Original 787-8 Block upgrades
  • LN7 – first customer airplane
  • LN100 – block entry point for family improvements as spin-off from 787-9 design
• Added complexity from engineering changes
  • LN7 block entry point for first block of weight saving items
  • LN7 block entry point for permanent center wing box fixes
  • LN20 block entry point for significant wing empty weight saving
  • LN20 block entry point for max takeoff weight increase and strengthened structure (might also conceal a major impact of the center wing issue)
• Added complexity from schedule slips
  • 787-9 design on hold pending availability of 787-8 ground and flight test data
    • Ground and flight loads data essential to calibrate FEM models
    • Aero and engine performance essential to determine need for additional weight savings
• Conundrum: Either wait for 787-9 design spin-offs to limit number of low-value “wave one aircraft” … or ramp up fast to recover delay in deliveries to customers
787-9 Engineering Changes - April 2008

200804BCA_787_Program_Update_787-9_weight_Spec_K+

787-9 Configuration Features
(Major Changes from 787-8)

- 280 seats (tri-class, 9 abreast economy class)
- Longer raked wing tip (wing span increased to 207.9 ft)
- New outboard slat
- Wing tip structure revised
- Wing structure strengthened
- Revised high lift actuation
- Composite ribs (on selected ribs)
- Structural fuel vent stringers (on selected stringers)
- Revised horizontal tail structural architecture (centerline splice, six-spar arrangement)
- Avionics/Flight Control systems revised due to 787-9 design
- Transport elements lengthened and revised over the wheel well
- Cargo ECS revised
- Fuselage structure strengthened
- Section 43 and 46 lengthened 5 frames (126 in.) each
- Wheel well pressure deck raised and architecture revised
- Section 47/48 join and Section 48/48 join re-designed
- Hybrid Ti-sine wave floor beams
- Maximum engine takeoff thrust rating (BET) increased to 73,800 lbs (RR) / 74,100 lbs (GE)
- Engine and nacelle support structure strengthened
- Landing gear strengthened
- Larger main landing gear truck
- Larger main landing gear wheels, tires, and brakes
- MLG retract actuation revised
- Cargo capacity increased to (6) pallets or (20) LD-3 forward; (5) pallets or (16) LD-3 containers aft

Design Weights:
- MTOW = 545,000 lb
- MLW = 425,000 lb
- MZFW = 400,000 lb
787-9 Configuration Features
(Major Changes from 787-8)

Fuselage
- Section 43 and 46 lengthened 5 frames (120 in., 3.1m) each
- Strengthened structure
  - Aft body join re-designed
  - Pi-box seal tracks
  - Hybrid Ti-sine wave floor beams
  - One-piece frame architecture

Wing
- Longer raked wing tip (wing span increased to 207.9 ft, 63.3m)
- Strengthened structure
  - Composite wing ribs
  - Vent stringers

Horizontal tail
- Revised structural architecture (centerline splice, six-spar arrangement)

Systems
- Hybrid air/vapor cycle cabin air conditioning system architecture
- Increased power generation to APU starter/generators (250 KVA)
- Cargo ECS revised

Design Weights:
- MTOW = 545,000 lb (247.2t)
- MLW = 425,000 lb (192.8t)
- MZFW = 400,000 lb (181.4t)

Engine thrust
- Maximum engine takeoff thrust rating (BET) increased to 73,800 lbs (RR) / 74,100 lbs (GE)

Landing gear
- Wheel well pressure deck raised and architecture revised
- Larger main landing gear truck
- Larger main landing gear wheels, tires, and brakes

Cargo capacity increased
- (6) pallets or (20) LD-3 forward
- (5) pallets or (16) LD-3 aft

Drag reduction
787 Program Schedule – April 2008

200804BCA_787_Program_Update_787-9_weight_Spec_K+

787-8
- Firm Configuration
- Rollout
- First Flight
- Delivery

2004 2005 2006 2007 2008 2009
- Prelim. Loads
- Validation Cycle WTT*
- Flight Loads
- Static Test Complete
- High Speed Lines Freeze
- Firm Configuration
- Delivery

787-9
- Wind tunnel testing
- Design Loads
- LN100
- Block Upgrade
- April 2008 Prod Schedule

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Backup
787 Body Section Overview

- Moveable Trailing Edge (HdH)
- Vertical Fin (Boeing-Fredrickson)
- Horizontal Stabilizer (Alenia)
- Aft Fuselage (Vought)
- Wing-to-Body Fairing (Boeing-Winnipeg)
- Fixed Trailing Edge (KHI)
- Center Fuselage (Alenia)
- Leading Edge (Spirit)
- Forward Fuselage (Spirit)
- Forward Fuselage (KHI)
- Center Wing Box (FHI)
- Main Landing Gear Wheel Well (KHI)
- Wing Box (MHI)
- Wing Tips (KAL-ASD)
- Wing Tips (KAL-ASD)
787-8 design weight improvements

Increase design weights:
MTOW = 502,500 lbs (227.9t)
MLW  = 380,000 lbs (172.4t)
MZFW = 355,000 lbs (161.0t)

Strngthened Airframe:
- Wing Leading Edge
- Outboard Wing
- Wing Center Section
- Wheel Well
- Center Fuselage

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