System Thinking & the Inevitability of the Dreamliner Delays

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Outline

• The 787 disaster
• The 787 development chain
• What happened? What really happened?
• Why? The truth behind the scenes!
• How to fix it?
787 Program – Overview

• Product specs
  – Composite materials: 50% by weight, 80% by volume
  – Lighter weight
  – Less fuel & emission
  – Easier maintenance
  – Larger cargo space
  – Cost less to run & maintain

• Development specs
  – 65% of design work is outsourced
  – Globally designed and fabricated: ≥ 100 suppliers, 12 countries
  – Tier 1 suppliers design and fabricate 11 major subassemblies
  – Boeing integrates & assembles

Budget ~ $10 Billion, Duration ~ 5 years
787 Program – Outcome

• The fastest-selling plane ever
  – Orders of 800~900 planes ~ $150 billion
• Significant delay
  – 1st flight: 28 months
  – 1st delivery: 40 months. 104 months (787) vs. 64 (777)
• Significant cost overrun (≥ $11 billion by 9/2011)
  – Write-offs (~$2.5 billion), excessive R&D costs (≥ $3.5 billion),
    customer contract penalty (≥ $5 Billion)
  – 7% orders were cancelled
• What caused the disaster?
• Could it have been avoided?
Conjectures

• Unions?
  – Union strike delayed 3 out of the 40 months total

• Technology?
  – The composite materials were applied to 737 & 777
  – Only 3 out of 7 delays are due to unexpected technical issues

• Too much outsourcing?
  – Speculations at best yet proven by data and facts
787 Development Chain

- Vertical Fin – Boeing-Fredrickson
- Aft Fuselage (S47, S48) – Vought
- Center Fuselage (S44, S46) – Alenia
- Fixed Trailing Edge – KHI
- Horizontal Stabilizer – Alenia
- Forward Fuselage (S43) – KHI
- Forward Fuselage (S41) – Spirit
- Wing Tips – KAL-ASD
- Wing Box – MHI
- Leading Edge – Spirit
- Main Landing Gear Wheel Well – KHI
- Center Wing Box (S11) – FHI

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Suppliers’ Roles

• Suppliers are responsible for design and fabrication

<table>
<thead>
<tr>
<th></th>
<th>787</th>
<th>747</th>
</tr>
</thead>
<tbody>
<tr>
<td>Architecture</td>
<td>Boeing</td>
<td>Boeing</td>
</tr>
<tr>
<td>Parts design</td>
<td>Suppliers</td>
<td>Boeing</td>
</tr>
<tr>
<td>Interface design</td>
<td>Boeing defines interface, suppliers</td>
<td>Boeing</td>
</tr>
<tr>
<td></td>
<td>provide detailed design, Boeing serves</td>
<td></td>
</tr>
<tr>
<td></td>
<td>as referee</td>
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</tbody>
</table>

• Benefits
  • Market: significant expansion ➔ reduce the unit cost
  • Technology: utilize the best in-class expertise & knowledge
  • Duration: parallel design of subsystems reduces R&D time
New Challenge – Incentive & Coordination

- Each company optimizes for itself but not for the project
  - Everyone tends to work slower and put in less effort
  - Or pass its unfinished work to others
  - How to align the incentives in a joint development project?

A Multi-Firm Project
Nature Of Development Work

• Development requires iterations & integration

• Requirement on coordination
  – Need the suppliers to hold on to the end and share the outcome
  – Need to motivate the suppliers to work hard and cost efficiently
Risk Sharing Partnership – Stakeholders

<table>
<thead>
<tr>
<th>Non-recurring development cost</th>
<th>Risk Sharing (787)</th>
<th>Subcontracting (747)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paid by suppliers</td>
<td>Paid by Boeing</td>
<td></td>
</tr>
<tr>
<td>When a supplier gets paid</td>
<td>When the project is done</td>
<td>When the job is done</td>
</tr>
<tr>
<td>Intellectual Property</td>
<td>Owned by suppliers</td>
<td>Owned by Boeing</td>
</tr>
<tr>
<td>Payment terms</td>
<td>Fixed price/unit</td>
<td>Fixed price/unit</td>
</tr>
</tbody>
</table>

- Alenia ($590 million), Japanese Heavies ($1.6 billion), Boeing ($4.2 billion), Global Aeronautica (GA), Spirit, Vought ($3.1 billion)
Benefits to Boeing

- Reduce upfront non-recurring R&D cost
- Reduce the loss of program delays
- Suppliers share the loss of delays ➔ they may work harder and more efficiently

- Boeing was so confident of the partnership, …

<table>
<thead>
<tr>
<th>Who select &amp; control tier-2 suppliers</th>
<th>787</th>
<th>747</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tier-1 suppliers</td>
<td></td>
<td>Boeing</td>
</tr>
<tr>
<td>#</td>
<td>Time</td>
<td>Duration</td>
</tr>
<tr>
<td>----</td>
<td>------------</td>
<td>-----------</td>
</tr>
<tr>
<td>1</td>
<td>10/2007</td>
<td>7 mon. on the 1st flight</td>
</tr>
</tbody>
</table>
## 2\textsuperscript{nd} and 3\textsuperscript{rd} Delays

<table>
<thead>
<tr>
<th>#</th>
<th>Time</th>
<th>Duration</th>
<th>Direct Causes</th>
<th>Who Resp.</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1/2008</td>
<td>3 months on the 1\textsuperscript{st} flight</td>
<td>Unfinished work from the suppliers. Slow assembly progress at Boeing</td>
<td>Vought Alenia GA Boeing</td>
<td>Suppliers: the same. Boeing: “we underestimated how long it takes to do someone else’s work”</td>
</tr>
<tr>
<td>3</td>
<td>4/2008</td>
<td>6 months on the 1\textsuperscript{st} flight</td>
<td>Continuing problems with unfinished work from suppliers</td>
<td>Vought Alenia GA Boeing</td>
<td>Same</td>
</tr>
</tbody>
</table>
# 4\textsuperscript{th} and 5\textsuperscript{th} Delays

<table>
<thead>
<tr>
<th>#</th>
<th>Time</th>
<th>Duration</th>
<th>Direct Causes</th>
<th>Who Resp.</th>
<th>Explanations</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>12/2008</td>
<td>6 months on the 1\textsuperscript{st} flight</td>
<td>Wrongly installed fasteners at Boeing FAL</td>
<td>Boeing</td>
<td>Poorly written instructions by Boeing engr. misled its workforce</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>6/2009</td>
<td>Indefinitely on the 1\textsuperscript{st} flight</td>
<td>Defects at wing-body joint</td>
<td>Boeing Fuji Mitsubishi</td>
<td>Structural flaw in design and engineering</td>
</tr>
</tbody>
</table>

- 1st test flight on 12/15, 2009
### 6th and 7th Delays

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<thead>
<tr>
<th>#</th>
<th>Time</th>
<th>Duration</th>
<th>Direct Causes</th>
<th>Who Resp.</th>
<th>Explanation</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8/2010</td>
<td>3 months on the 1st delivery</td>
<td>Uncontained engine failure &amp; availability issue</td>
<td>Boeing Rolls Royce</td>
<td>Unknown</td>
</tr>
<tr>
<td>7</td>
<td>12/2010</td>
<td>Indefinitely on the 1st delivery</td>
<td>An on-board electrical fire</td>
<td>Hamilton Sundstrand</td>
<td>Foreign debris in e-cabinets</td>
</tr>
</tbody>
</table>

- Out of the 7 major delays, only 3 are due to technical issues, 4 of them are due to “irrational behaviors” of Boeing and its suppliers.
Summary of Irrational Behaviors I

- Boeing selected Vought to design and manufacture the world’s 1st all-composite aft-fuselage, but Vought had no engineering department when selected.
- GA used low-wage, trained-on-the-job workers with no aerospace experience to assemble fuselage sections, and didn’t train them for FAA compliance until the job is past-due.
- Vought had to use novice student inspectors because it had problems attracting competent technicians.
- Alcoa quoted a lead time of 60 weeks for fasteners, citing issues of capacity & scale economies, contributing to the first delay. In response, Boeing aggregated fastener procurement, ensuring favorable pricing.
Summary of Irrational Behaviors II

- Tier-2 suppliers lack of Q/A equipment and personnel to do testing at component and subsystem levels. Tier-1 suppliers deferred testing to FAL
- Production records on suppliers’ work were found incomplete or lost in transfer resulting in a loss of configuration control
- Poorly written instructions led to the embarrassing wrongly installed fasteners at Boeing
- ...
- Obvious mistakes – Boeing and its suppliers must know!
Hypothesis Testing

- **Null hypothesis**: Boeing and its suppliers were fully committed to the 787 program and are really concerned about the delays.

- **Alternative hypothesis**: They were not …

- **Test statistic**: The slips (man-made errors) and their impact

- **Obvious mistakes** – Boeing and its suppliers must know!
- If the null hypothesis is true, would any of these happen?
- **Knowing it was wrong, why did they still do it?!**
Cost Analysis

- Direct cost (~ task duration)
  - Competent management organization
  - Workforce & training
  - Equipment
  - Materials
  - Transportation

- Shorter task duration ➔ higher direct cost

- Indirect cost (~ project duration)
  - Overheads (utilities, facilities, benefits)
  - Cost of capital, interests
  - Contract penalty
  - Order cancellation

- Longer project duration ➔ higher indirect cost
Risk Sharing Partnership

- The firms pay the **up-front investment** and get paid **when the project is done**
- If a firm works slower and delays its task
  - The firm saves on its **direct cost**, e.g., labor, shipping, materials
  - None gets paid on-time and all suffer a higher **indirect cost**
  - Firms on time are penalized by other’s delay
  - The delayed firm is not fully responsible for the damage
- If I can benefit from a delay & have others share the damage, I tend to delay
  ➔ **moral hazard**
**A Simple Example**

<table>
<thead>
<tr>
<th>Task</th>
<th>Immediate Predecessor</th>
<th>Description</th>
<th>Normal Duration ($d$)</th>
<th>Maximum Duration</th>
<th>Saving /Week ($s$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-</td>
<td>Longer but technically not intensive</td>
<td>9 weeks</td>
<td>10 weeks</td>
<td>$900</td>
</tr>
<tr>
<td>B</td>
<td>A</td>
<td>Shorter but technically intensive</td>
<td>5 weeks</td>
<td>6 weeks</td>
<td>$1200</td>
</tr>
</tbody>
</table>

Due in 14 weeks.
Extra indirect cost/week: $p = $1600
Global Optimum

- One company conducts all tasks and optimizes for the entire project
- The optimal solution:
  - On time, no delays
  - Optimal project duration = 14 weeks
  - Loss = $0

A → 2
Duration 9 → 10 weeks,
saving $900

B → 3
Duration 5 → 6 weeks,
saving $1200

Due in 14 weeks. Extra indirect cost/week: $p = $1600
Risk-Sharing I

• **Win-Lose** scenarios
  – If A delays but B is on time, what happens?
  – A’s payoff: $150; B’s payoff: −$850
  – Similar results if A is on time but B delays

• **Lose-Lose** scenario
  – Both A and B delay
  – A’s payoff: $900−$1500=−$600; B’s payoff: $1200−$1700=−$500

Due in 14 weeks
Extra indirect cost/week,
A: $p_A = $750
B: $p_B = $850
Risk-Sharing II

- **Win-Win scenario**
  - Both A and B are on time – a mutually beneficial deal
  - Project duration: 14 weeks
  - A’s payoff: $0; B’s payoff: $0

Due in 14 weeks
Extra indirect cost/week,
A: \( p_A = $750 \)
B: \( p_B = $850 \)
## Risk-Sharing – Actions & Payoffs

<table>
<thead>
<tr>
<th>Firm A</th>
<th>Firm B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Keep</strong></td>
<td><strong>Delay</strong></td>
</tr>
<tr>
<td>A: $-750</td>
<td>A: $0</td>
</tr>
<tr>
<td>B: $350</td>
<td>B: $0</td>
</tr>
<tr>
<td>(Lose-Win)</td>
<td>(Win-Win)</td>
</tr>
<tr>
<td><strong>Delay</strong></td>
<td><strong>Keep</strong></td>
</tr>
<tr>
<td>A: $-600</td>
<td>A: $150</td>
</tr>
<tr>
<td>B: $-500</td>
<td>B: $-850</td>
</tr>
<tr>
<td>(Lose-Lose)</td>
<td>(Win-Lose)</td>
</tr>
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</table>

Guess what is the final outcome?
The Prisoners’ Dilemma

- **Win-Lose** is clearly not stable
- **Win-Win** seems plausible but indeed unstable
  - Each firm will find every excuse to delay
  - Why – A’s optimal decision is to delay regardless of the B’s action; similar result applies to B.
- **Lose-Lose** is stable and the outcome
  - Prisoners’ dilemma – Nash equilibrium

- **Summary:** although being on time benefits the entire project, it is in each company’s interest to delay

- For a general theory on this Prisoners’ Dilemma, please see Xu and Zhao (2013)
Reconciliation

• 787 program resembles the example
  – Suppliers develop subsystems
  – Boeing assembles and integrates

• Our analysis (Prisoner’s Dilemma) reveals
  – Under risk sharing, Win-Win is not stable, Lose-Lose is the equilibrium!

• Practical evidence?
• Let’s recall the irrational behaviors, …
The Truth Behind The Scenes – Suppliers

• Suppliers’ excuses for delays
  – Lack of testing and Q/A equipment and personnel
  – Low-wage, train-on-the-job workers
  – Inability to attract competent technicians, have to use novice student inspectors
  – No inventory oversight
  – Workers lack of training & FAA compliance
  – Incomplete documentation or lost in transit
  – Vought waited till the last moment (May 2006) to build the plant (job due May 2007)
  – Alcoa quoted a 60-week lead time for fasteners
  – …

• Were they not able to do their jobs well or didn’t want to do it well?

What did they really say?

Reconciliation
The Truth Behind The Scenes – Boeing

• Boeing’s excuses for delays
  – Alcoa quoted a 60-week lead time for fasteners (citing capacity issues & economies of scale)
  – Boeing consolidated its fastener procurement, directly negotiated with suppliers, for favorable pricing
  – Selected Vought who has no engr. dept. to do the most technical work
  – “We underestimated how long it takes to do someone else’s work” – slow progress at FAL to fix the traveled work
  – Embarrassing wrongly installed fasteners – poorly written doc. by Boeing Engr. misled its workforce
  – ...

• Was Boeing really concerned about the delays of the 787 program or just its own cost & risk?
System Thinking and The Inevitability

• These behaviors are irrational to the 787 project.
• But they can be rational for each individual firm!
• What is best for each firm ≠ what is best for the project.
• What really happened: each firm tends to delay behind the schedule because it can save its direct costs and have other firms to share the extra indirect cost incurred by its delay (moral hazard).

• Knowing it was wrong for the project, Boeing and the suppliers still did it because it was in their best interest → the delays were inevitable.
How to Fix It?

• Outsourcing of design and fabrication is irreversible

• How to align incentives in joint development projects?
  – Why didn’t Boeing penalize the suppliers for their delays?
Uncontrollable Delays

- Technical challenges
- Natural disasters
- Union strikes

Sharing the risk of uncontrollable delays
- Fair, none should be blamed for technical impossibilities
- Reduces each firm’s risk → the portfolio effect
Controllable Delays

• Careless lapses
• Mis-management
• Firms’ strategic behaviors

Avoidable by extra efforts & commitment

• Sharing the risk of controllable delays
  – Unfair, why should I be responsible for others’ mistakes?
  – Encourages such delays ➔ suboptimal project performance in both time and cost
Fair Sharing Partnership I

- We share the risk of uncontrollable delays, but have each firm fully responsible for its controllable delays
  - If firm A delays, it bears $p_A$ and pays firm B $p_B$ (B’s damage due to A’s delay)
  - Win-win is the equilibrium!

<table>
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<th>Duration</th>
<th>Saving</th>
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<tbody>
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<td>$900</td>
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</table>

Due in 14 weeks
Extra indirect cost/week,
A: $750
B: $850
Fair Sharing – Not A Panacea

• Distinguish between controllable and uncontrollable delays

• Fair sharing may not work when
  − It is hard to distinguish the controllable and uncontrollable delays
  − Projects of creative activities and high technical challenges
Recap

• Jigsaw puzzle – they did it on purpose

• Prisoner’s Dilemma – it was in their best interests

• Risk analysis – they shared the wrong risk
For More Information

- [http://zhao.rutgers.edu/](http://zhao.rutgers.edu/)
- [yaozhao@andromeda.rutgers.edu](mailto:yaozhao@andromeda.rutgers.edu)
- My case study: [Build-to-Performance – the Boeing 787 Dreamliner](http://zhao.rutgers.edu/)
- Any questions and comments are welcome!