Why 787 Slips Were Inevitable?[1]

Yao Zhao, PhD

Associate Professor in Supply Chain and Project Management

Rutgers, the State University of New Jersey

yaozhao@andromeda.rutgers.edu

Abstract: Boeing 787, the Dreamliner, was the fastest-selling plane ever in the commercial aviation industry. However, its development was a nightmare – the first flight was delayed by 26 months and the first delivery was delayed by 40 months with a cost overrun of at least $10 Billion. By a comprehensive empirical study of the actual events and facts, we find strong evidence to suggest that a majority of the delays were intentional. An analysis of economic drivers in joint development projects discovers that the 787's risk-sharing partnership forced Boeing and its partners to share the "wrong" risk. This led the firms into a Prisoner's Dilemma where delays were in the best interests of these firms although doing so drove them into a disaster. We reconcile the analysis with the empirical evidence to reveal the rationale behind many seemingly irrational behaviors that delayed this program. Finally, we suggest a new "fair sharing" partnership to share the "right" risk and greatly alleviate delays for development programs of this kind.

Key words: innovation, joint ventures, product development, supply chain, manufacturing.

1. Introduction

On September 26, 2011, Boeing Company publicly announced the delivery of its first 787 Dreamliner to its launching customer, All Nippon Airways, after a 40-month of agonizing delay. The actual development cost of the program was estimated at about $40 billion and was "well more than twice the original estimate" (Mecham 2011).

The Dreamliner is believed to be the most advanced commercial aircraft ever built and the most efficient to operate. It was the fastest-selling plane ever in the commercial aviation industry (Tang and Zimmerman 2009) with a total order of 800~900 planes before its 1st flight, which worth about $150 billion (Kotha and Nolan 2008). However, its development was a nightmare as it suffered repeated delays and a significant cost overrun. This event has a widespread impact on the commercial aviation

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industry and aroused the curiosity of the entire world. Naturally, people asked, what caused the delay? How could it have been avoided?

In this article we analyze Boeing's traumatic experience, discover what really happened, identify the root causes, and offer ways to avoid similar failures in the future. We believe that such lessons can provide valuable insights for large companies around the world to ensure future successes in complex projects developed jointly with suppliers.

Our conclusion is simple. A majority of 787's delays were intentional and thus could have been avoided. The root cause of these delays is the risk sharing partnership which forced Boeing and its partners to share the "wrong" risk and thus led them into a subtle but deadly trap where these firms are motivated to delay in their own best interests. Properly distinguishing different types of risk and sharing the "right" risk selectively can help aligning the interests of individual firms with that of the project and thus significantly reduce or completely avoid such deliberate delays.

For our methodology we use an integrated empirical-analytical approach where we combine a comprehensive empirical study of the actual events and facts with an economic analysis of financial incentives, gaming and risk in joint development programs. Reconciliation between the empirical evidence and the analysis reveals the true rationales behind many seemingly irrational behaviors that delayed the 787 program, and enlightens the ways to avoid similar disasters in the future.

We start by describing the background and the 787's development chain to find out how 787 was developed and how the program was managed. This is followed by a thorough empirical study on the delays where we match up pieces of fragmented information to constitute the whole picture on what really happened. We then conduct an economic analysis to understand the firms' financial incentives and unveil the trap induced by the risk sharing partnership. The main sections of this article reconcile the empirical evidence with the economic analysis to reveal the root cause for the delays, and suggest a new partnership to avoid the trap by sharing various types of risk in development projects "fairly". We conclude by discussing what lessons large development programs could learn from Boeing's experience in collaborative innovations.

2. Background

2.1. 787 Unique Features

787, the Dreamliner, is Boeing's next generation commercial aircraft targeted at the aviation market segment of rapid, direct and point-to-point connections. The Dreamliner is unique in its extensive use of the lightweight composite materials, which account for about 50% of the airplane by weight, and 80% by volume (Teresko 2007). As a comparison, the Boeing 777 airplane has 12% of the composite materials by weight. The composite materials provide the Dreamliner two distinct advantages: (i) light weight, which means fuel efficiency, and (ii) easy maintenance. So the Dreamliner was designed to cost less to operate and maintain than the current generation aircrafts.

2.2. The 787 Development Chain

The Dreamliner is unprecedented in the scale of development outsourcing – 65% of the development work is outsourced to more than 100 suppliers from 12 countries (Horng and Bozdogan 2007, Exostar 2007). Tier 1 suppliers design and fabricate 11 major subassemblies, Boeing integrates and assembles. Most notably, the nose-and-cockpit section was outsourced to Spirit, the forward fuselage was outsourced to Kawasaki from Japan, the center fuselage was outsourced to Alenia from Italy, and the after fuselage was outsourced to Vought. The wing and wing box were outsourced to companies from Japan, Korea and Australia. Many smaller parts are also outsourced, such as the landing gear, fairing and doors. Exhibit 1 provides details on tier-1 suppliers.

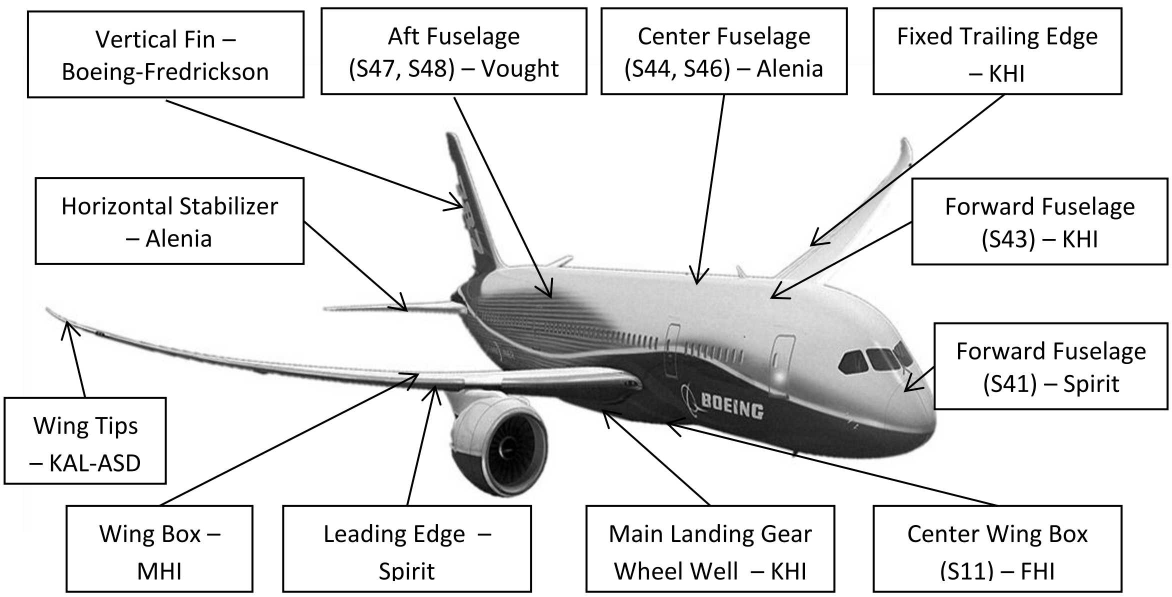

Exhibit 1: The 787 tier-1 suppliers.

The suppliers are responsible for both design and fabrication of the parts. Specifically, Boeing defines the parts and interfaces, the leaves the detailed design to tier-1 suppliers who can optimize within each work package, and must work with each other on the interfaces. In case of disputes, Boeing serves as a referee to assist the suppliers; but in the end, the suppliers need to make the designs by themselves (Horng and Bozdogan 2007).

	787	**747**
Architecture	Boeing	Boeing
Parts design	Suppliers	Boeing
Interface design	Boeing defines interface, suppliers provide detailed design, Boeing serves as referee	Boeing

Exhibit 2: Boeing and the suppliers' role in the 787 development.

Development (design and fabrication) outsourcing provides Boeing significant benefits:

1. Market expansion. It is well known that developing a new airplane requires a significant up-front investment for R&D, engineering, construction and testing. One has to recoup these costs from sales

by spreading them among the planes sold. If one cannot sell enough planes, the unit cost would be too high for any airline to afford it. The most effective way to sell the airplane to other countries is to have manufacturers from those countries participate in the development, the so-called offset deals. Development outsourcing is instrumental in making the Dreamliner the fastest-selling plane ever in the commercial aviation industry.

2. Technology: Development sourcing enables Boeing to utilize the best in-class expertise and knowledge worldwide, and thus reduces the technological risk.
3. Duration: Parallel development of subsystems can help Boeing reduce the total development cycle time.

Because of these benefits, the trend of outsourcing (design, fabrication, or both) is irreversible in the Aerospace and Defense industry. Besides 787, noticeable examples are Airbus 380 and the Global Hawk (Ulder 2011). Statistics shows that, on average, about 50% of the revenue of Raytheon was paid to the suppliers (Kamath 2010).

2.3. The Risk Sharing Partnership

While indispensable, global outsourcing introduces a significant new challenge – incentive and coordination in a joint development project. Unlike the 1960s-70s when one firm did all, today different tasks that constitute a project are performed by different firms who rely on each other to control their cost and schedule (see Exhibit 3 for an example, where firm B can only start after firm A completes its tasks, and may have to watch out for firm D's completion time to determine its task duration).

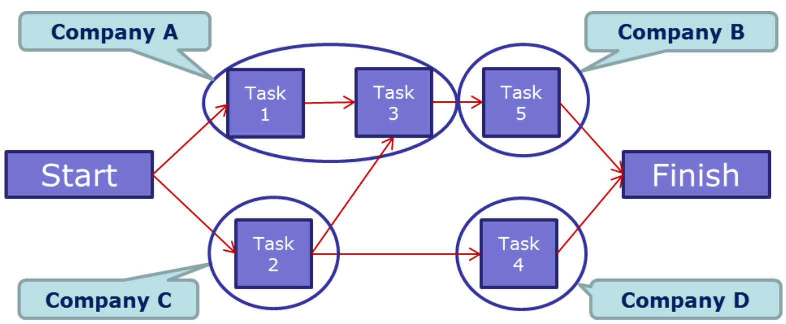

Exhibit 3: A joint development project.

The most significant issue of a joint development project is that each firm ultimately optimizes only for its own benefit rather than the benefit of the project. For instance, firms may put in less effort and slow down their work, or even pass their incomplete work to others. Thus, the question is, how to align the incentives in a joint development project?

To answer this question, we must understand the nature of development projects. Development projects typically require iterations & integrations, thus it can be hard to estimate the total cost and time for such a project. To coordinate the efforts in a development project, Boeing has to require the suppliers to hold on to the end of the project and share the outcome. This requirement rules out the fixed price contracts (as in subcontracting) where the suppliers are paid upon job completion, and thus can walk away from future iterations. Second, Boeing must motivate the suppliers to work hard and cost efficiently. This requirement rules out the time-material contracts (as in consulting), which may encourage the suppliers to work slowly and inflate their cost.

Boeing understood these requirements well and came up with an ingenious idea – the risk-sharing partnership, which makes the suppliers the stakeholders of the 787 program (Horng and Bozdogan 2007, Tang and Zimmerman 2009). Specifically, Boeing asked the risk-sharing partners to bear the up-front non-recurring R&D investment for their tasks, and wait until the plane is certified and delivered to get paid. So the suppliers have to share the risk of program delays. The payment follows a pre-negotiated price per unit, and so the more planes Boeing sells, the more money each supplier makes. To compensate the suppliers for taking the risk, Boeing assigned them the intellectual property rights of their parts, and so the suppliers have the assurance from Boeing that they will not be replaced down the road. Exhibit 4 summarizes the risk sharing partnership.

	Risk Sharing (787)	**Subcontracting (747)**
Non-recurring development cost	Paid by suppliers	Paid by Boeing
When a supplier gets paid	When the project is done	When the job is done
Intellectual Property	Owned by suppliers	Owned by Boeing
Payment terms	Fixed price per unit	Fixed price per unit

Exhibit 4: The risk-sharing partnership.

Suppliers share more than half of the upfront non-recurring R&D investment (Lee and Anupindi 2009) which can be broken down as follows: Alenia ($590 million), Japanese Heavies ($1.6 billion), Global Aeronautica (GA), Spirit, Vought ($3.1 billion), and Boeing ($4.2 billion).

The risk-sharing partnership promised tremendous benefits to Boeing: first, it reduces substantially Boeing's upfront non-recurring investment. Second, it reduces Boeing's exposure to financial risks because if the project is ever delayed, Boeing only bears the loss of its own investment while suppliers have to pay for theirs. Finally, suppliers may have an incentive to work efficiently and hard because they are spending their own money and sharing the loss of delays.

The combination of development outsourcing and the risk-sharing partnership (dubbed "Build-to-Performance") looks like a wonderful idea. Boeing was so confident of the partnership that it left the selection and control of the subtier suppliers to its risk sharing partners (Horng and Bozdogan 2007).

2.4. The 787 Disaster and Conjectures

In reality, the development of the Dreamliner was a disaster – the first flight was delayed by 26 months and the first delivery was delayed by 40 months. Accompanied with the delays is the significant cost overrun. Estimates vary by agencies; conservatively, the overrun of Boeing's development cost is at least $11 billion by the first delivery (Gates 2011), including, write-offs due to defects (~$2.5 billion), excessive R&D costs, supplier support and buy-out (≥$3.5 billion), customer contract penalty (≥ $5 Billion). In addition, about 7% of the orders were cancelled before the first delivery (Xu and Zhao 2010).

It was truly a nightmare as compared to other programs recently launched in the commercial aviation industry. Exhibit 5 provides a comparison among Boeing 777 (Lane 1995), Airbus 380 (Clark 2006) and Boeing 787 programs (Xu and Zhao 2010).

	Official launch date	Date of the 1st firm order	Planned 1st delivery date	Planned program duration (months)	Actual 1st delivery date	Actual program duration (months)	Delay of the 1st delivery (months)	Total Development cost (all firms involved)
777	1/1990	10/1990	5/1995	***64***	5/1995	***64***	***0***	***~$6-7 billion***
380	12/2000	12/2000	2/2006	***62***	10/2007	***82***	***20***	***~$13 billion***
787	1/2003	4/2004	5/2008	***64***	9/2011	***104***	***40***	***≥ $20 billion***

Exhibit 5: Performance comparison among Boeing 777, Airbus 380 and Boeing 787.

The industry and academia were heavily debating on the causes of the delays. In the end, they came down to three conjectures:

1. Union strikes (e.g., Kotha and Nolan 2008). The mechanistic unions are powerful forces in this industry. But if we look at the actual events and facts, union strikes only delayed 3 out of the 40 months total (Turim and Gates 2009). So the unions had an impact but not substantial.
2. Technical issues. People argued that the composite materials have never been applied so extensively to a plane of this size (e.g., Tang and Zimmerman 2009, Shenhar, et al. 2012). True, but the composite materials were not new as they were applied to the 737 and 777 programs. In fact, the 777 airplanes have 12% of composite materials by weight (Horng and Bozdogan 2007). Most importantly, a comprehensive examination of the actual events and facts shows that only 3 out of a total 7 major delays are probably due to unexpected technical issues.
3. Too much outsourcing. This is the most popular conjecture given the numerous lapses of the suppliers in this program (see, e.g., Weitzman 2011, Hiltzik 2011, Kotha and Nolan 2008, Tang and Zimmerman 2009). However, the claim is at best a speculation yet proven by the actual events and facts.

3. The Empirical Study: What Really Happened?

In January 2003, Boeing set up a team of executives to design and sell a new plane, which was later renamed the 787 Dreamliner. The original plan is to have the suppliers complete and deliver all subsystems by June 2007. Boeing will integrate and assemble the plane in June-July 2007. The 1st flight will be tested in August 2007, and the 1st delivery will be made in May 2008 (Turim and Gates 2009). The planned duration for the 787 program is 64 months, comparable to the actual duration of Boeing's last mega project, the 777 program. In reality, the 1st flight was delayed to December 2009 (late by 26 months) and the first delivery was postponed to Sept. 2011 (late by 40 months). In the end, the total development time of the Dreamliner is 104 months as compared to the 64 months of the 777 program.

3.1. Actual Events and Facts: What Happened?

We shall start by examining the status of the first "assembled" Dreamliner (LN 1) rolled out for the 787 premiere in July 2007. Unknown to the public at the time, the plane was a hollow shell, even some of the outer structure is fake, e.g., the wing slats are painted wood (Turim and Gates 2009). Let's open up the shell to see what was inside (Domke 2008, Kotha and Nolan 2008):

• After fuselage (by Vought) structure is 16% complete, systems integration 0%
• The nose-and-cockpit session and the forward fuselage (by Spirit & Kawasaki) sagged out of shape in transit due to incomplete frame and floor beam installation
• Redesign for interfaces: Aft body joint S47/S48, Aft body joint S48/S48 (APU cone), and center body joints S11/S44/S45/S46
• Due to a fastener shortage issue, temporary fasteners were used for the first few 787s. However, the replacement of these temporary fasteners is hampered by a lack of documentation
• 35 part numbers are still missing by July 2008
• LN1 primary structure is not completed by August 2008

Exhibit 6: LN 1 status upon entering the final assembly line, May, 2007.

Should you know what was inside LN 1, you won't be surprised by the subsequent delays. The following table summarizes each major delay by duration, direct causes, firms responsible and their explanations (Xu and Zhao 2010).

#	Time anno-unced	Duration	Direct Causes	Who Respo-nsible	Explanations
1	10/ 2007	7 months on the 1st flight	Parts shortage (e.g., fasteners).	Alcoa Vought Alenia Spirit GA Honey-well etc.	Issues with production capacity & scale economies.
			Defects. Unfinished work from suppliers.		Lack of testing & Q/A equipment & personnel, workers lack of training and FAA compliance, had to use student inspectors.
			Design issues		Vought had no engineering dept. when selected
			Missing Documentation.		Suppliers had to rush to meet the schedule, so … (Kotha & Nolan 08)
			Flight control software.		The supplier underestimated the time (Kotha & Nolan 08)
2	1/ 2008	3 months on the 1st flight	Unfinished work from the suppliers.	Vought Alenia GA Boeing	Suppliers: the same.
			Slow assembly progress at Boeing		Boeing: "we underestimated how long it takes to do someone else's work"
3	4/ 2008	6 months on the 1st flight	Same as above	Same as above	Same as above

4	12/ 2008	6 months on the 1st flight	Wrongly installed fasteners at Boeing FAL	Boeing	Poorly written instructions by Boeing engineers confused and misled its workforce
5	6/ 2009	Indefinitely on the 1st flight	Defects at wing-body joint	Boeing Fuji Mitsubishi	Structural flaw in design and engineering
6	8/ 2010	3 months on the 1st delivery	Uncontained engine failure & availability issue	Boeing Rolls Royce	Unknown
7	12/ 2010	Indefinitely on the 1st delivery	An on-board electrical fire	Hamilton Sundstrand	Foreign debris in electric cabinets, and more, …

Exhibit 7: 787 major delays.

In summary, out of the 7 major delays, 3 may be caused by technical issues, 4 of them are caused by some "irrational" behaviors of Boeing and its suppliers, as summarized below.

The "irrational" behaviors	Why irrational?
Boeing selected Vought to design and manufacture the world's 1st all-composite aft-fuselage, but Vought had no engineering department when selected	How could Boeing select a firm with limited design and engineering capability to design and fabricate one of the most technical and novel parts?
General Aeronautica used low-wage, trained-on-the-job workers with no previous aerospace experience to assemble fuselage sections, and didn't train them for FAA compliance until the job is past-due	As a joint venture between two experienced aircraft manufacturers (Alenia and Vought), how could GA not know the very basics – training its workforce for the FAA compliance?
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	• No matter how sophisticated the fasteners are, they won't take 60 weeks to make. Alcoa was bargaining for a better deal • Rather than giving Alcoa a better deal to reduce the lead time, Boeing pressed Alcoa further on pricing, which prolonged the lead time.
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	What kind of engineering and manufacturing firms will design and fabricate a new part without testing it?
Vought (Charleston, SC) had to use novice student inspectors because it had problems attracting competent technicians	Using interns to assure the quality of the world's 1st all-composite aft-fuselage? No wonder why numerous defects have gone unnoticed.

Production records on suppliers' work were found incomplete or lost in transfer resulting in a loss of configuration control	As experienced aircraft manufacturers, how is it possible that they could forget production records or have them lost in transit?
Poorly written instructions led to the embarrassing wrongly installed fasteners at Boeing	How is it possible that Boeing, a company holding such a high reputation in engineering, messed up instructions for installing fasteners?

Exhibit 8: The "irrational" behaviors of Boeing and the suppliers.

3.2. Hypothesis Testing: What Really Happened?

Most people from either industry or academia believed that the delays were accidental, that is, Boeing and its suppliers have good intentions but made some mistakes inadvertently. To put it formally, the common null hypothesis (or belief) is

$$H_0: Boeing\ and\ its\ partners\ were\ fully\ commited\ and\ really\ concerned\ about\ the\ delays.$$

The opposite of this hypothesis (the alternative hypothesis) is,

$$H_a: they\ were\ not.$$

To test these hypotheses, we examine the slips (due to human errors or mismanagement) and their impact on program performance. If H_0 is true, then these slips should be rare and even if they occur, their impact should be minimum as Boeing and its partners would do their best to mitigate it.

However, our empirical study in §3.1 shows the opposite: numerous slips of both Boeing and its suppliers accounted for a majority of the delays (at least 4 out of the 7 major delays, for at least 22 out of a total 40-month delay) and are caused by such errors and mismanagement as unable to hire competent technicians, cannot prepare well and keep safe production records and documentations, forgot to train their workers for FAA compliance, and a lack of equipment and personnel to do quality assurance, etc. (see Exhibit 8 for the "irrational" behaviors). These errors are trivial because they are at the very basics of aircraft manufacturing. As well established and experienced aircraft manufacturers, it is impossible for Boeing and its partners to not know these errors and their consequences.

In conclusion, these errors are so obvious and common sense that Boeing and its suppliers must know. Thus, if H_0 is true, that is, Boeing and the suppliers were fully committed and really cared about the delays, none of these errors ("irrational" behaviors) would have occurred! And even if they do, they should have a minimum impact. However, in reality, they all happened and had a significant impact on the program, which implies that H_0 cannot be true and H_a must be true, that is, Boeing and the suppliers were not committed and didn't really care about the delays, contrary to their claims in public. Thus, the question here is not about how to correct these errors, but, **knowing it was wrong, why did they still do it?!**

4. The Economic Analysis: The Prisoners' Dilemma

4.1. Project Cost Structure

To understand the financial incentives and economic drivers that led the firms willingly into these errors, let's first analyze the firms' cost structure. Typically, there are two types of costs in a project (Nahmias 2004):

- Direct costs: including expenses spent on management organizations, workforce and training, equipment, materials, and transportation. One can reduce the direct costs by delaying the task.
- Indirect costs: including overheads (utilities, facilities, and benefit), capital costs, contract penalty, and order cancellations. One can reduce the indirect costs by completing the project earlier.

The direct and indirect costs move in the opposite directions as the project duration increases (Exhibit 9).

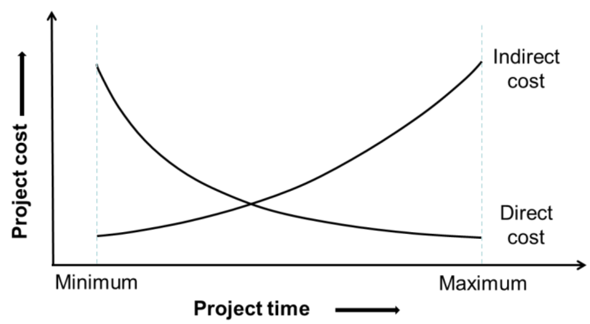

Exhibit 9: The direct and indirect costs.

Let's now understand the risk-sharing partnership from the cost perspective. Under this partnership, each firm pays the up-front investment for its task and gets paid when the whole project is completed. Thus, if a firm delays its task, it saves on its direct cost but everyone suffers a higher indirect cost due to the resulting project delay. Firms completed their tasks on time are penalized by the delayed firm, and thus the latter is not fully responsible for the damage caused by its delay. Intuitively, if one firm can benefit from a delay and have others share the damage, the firm tends to delay – this is the "moral hazard" issue in the classical economic literature (Holmstrom 1982).

4.2. The Prisoners' Dilemma

To understand the moral hazard issue and its potential impact in the project management settings, we consider a simple example analogous to the Dreamliner's workload distribution. In this example, we have two sequential tasks, A and B, for which, the planned durations are, say, 9 and 5 weeks (Exhibit 10). We can delay each task by one week, and save $900 (for A) and $1200 (for B) in the direct costs. But if the project is delayed behind the delivery due date, which is 14 weeks, the project suffers an extra indirect cost of $1600 per week.

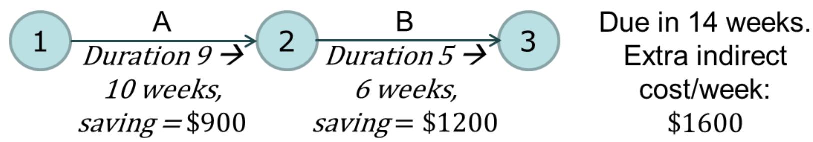

Exhibit 10: A simple example

In the "one-firm-does-all" model, one firm does both tasks. Then the firm would not delay any task because the extra indirect cost of the project upon delay exceeds the savings in the direct costs of all tasks.

In the outsourcing and risk-sharing model, let's assume that firm A does task A, firm B does task B, and upon each week of the project delay, firm A pays an extra indirect cost of $750 and firm B pays $850 (the total indirect cost is still $1600/week). Because the project duration depends on both firms' efforts, now each firm's cost and schedule depend on the other firm's action. To find out what firms A and B would do in their best interests, we study four possible scenarios:

1. (**Win-Lose**) If firm A delays but firm B keeps its task duration, then the project is delayed by one week. A saves $900 but loses $750 with a net gain of $150, while B suffers a net loss of $850. Essentially, firm B keeps up its task duration for firm A's benefit.
2. (**Lose-Win**) If firm A keeps its task duration but firm B delays, then the project is again delayed by one week. Firm A suffers a net loss of $750, while firm B saves $1200 but loses $850 with a net gain of $350. In this case, firm A pays a penalty for firm B's delay.
3. (**Lose-Lose**) if both firms A and B delay, then the project is delayed by two weeks because the tasks are sequential. Firm A incurs a net loss of $600 (= 2x$750 – $900) while firm B suffers a net loss of $500 (=2x$850 – $ 1200).
4. (**Win-Win**) Firms A and B can negotiate a mutually beneficial deal, in which, both keep their task durations and thus lose nothing.

Firm A \ Firm B	Delay	Keep
Keep	**A: –$750** **B: $350** **(Lose-Win)**	**A: $0** **B: $0** **(Win-Win)**
Delay	**A: –$600** **B: –$500** **(Lose-Lose)**	**A: $150** **B: –$850** **(Win-Lose)**

Exhibit 11: The scenarios and pay-offs of firms A and B.

Exhibit 11 summarizes the scenarios and the pay-offs of both firms. Clearly, the "Win-Lose" and "Lose-Win" scenarios are not feasible because no firm would sacrifice itself for the other's benefit. From the project's perspective, the "Win-Win" scenario is the best outcome because this is what a firm would do in the "one-firm-does-all" model. Under risk sharing, however, this scenario is unstable because each firm can be better off by delaying its task regardless of the other's action. Thus, each firm will find every excuse to delay. Although the "Lose-Lose" scenario is the worst outcome for the project, it is indeed stable and the final outcome (as in the Prisoner's Dilemma). This simple example reveals a deep insight: the risk sharing partnership can put the firms into a Prisoners' Dilemma – although keeping the planned duration benefits the entire project, it can be in each firm's best interests to delay. The same insight holds true in general systems with more realistic project networks and cost structures; see Xu and Zhao (2013) for a rigorous mathematical analysis.

5. Reconciliation: What Caused The Delays?

The 787 Dreamliner program resembles the simple example in §4 where the suppliers first develop subsystems and then Boeing assembles and integrates. Our analysis shows that the risk-sharing partnership may motivate the firms to delay their tasks against the best interests of the project. To reconcile the analysis with practical evidence, let's recall the "irrational" behaviors in §3.1. We shall first reveal the rationale (the ugly truth) behind the suppliers' behaviors by discovering what they really wanted to say (Exhibit 12).

Suppliers' "irrational" behaviors (excuses for delays)	*What did the suppliers really say?*	Reasoning
• **Lack of testing and Q/A equipment and personnel** • **Used low-wage, train-on-the-job workers to assemble fuselages** • **Inability to attract competent technicians, have to use novice student inspectors**	*I don't want to spend money on it*	• If you paid the salary of an intern, you only get interns. • If the suppliers really cared about their work, they shouldn't have saved money from necessary equipment and qualified personnel.
• **No inventory oversight** • **Workers lack of training & FAA compliance** • **Incomplete documentation or lost in transit**	*I don't care much to manage it well*	The FAA compliance training only takes a couple of days (Gates 2008). Even the documentation was lost in transit, how careless they were!
• **Vought waited till nearly the last moment (5/2006) to build the plant (job assigned 11/2003, due 5/2007)**	*I wish I could delay it more*	Vought took 2 ½ years to build the plant, only left itself 1 year to build the part. Recall that the part is only 16% complete (§3).
• **Alcoa quoted a 60-week lead time for fasteners, citing capacity issues & scale economies.**	*I only care about my thousand \$ setup cost but your million \$ plane*	Alcoa was reluctant to speed up production without obtaining a better volume and price deal from Boeing (Lee and Anupindi 2009)

Exhibit 12: The truth behind scenes for the suppliers.

The reconciliation clearly shows that the delays occurred not because the suppliers weren't able to do their jobs well but because they just didn't want or care enough to do it well. What happened is that these suppliers were delaying their jobs as much as possible and doing it in the cheapest possible way!

Let's now reveal the rationale behind Boeing's "irrational" behaviors by discovering what Boeing really wanted to say (Exhibit 13).

Boeing's "irrational" behaviors (excuses for delays)	***What did Boeing really say?***	**Reasoning**
Alcoa quoted a 60-week lead time for fasteners, citing issues of capacity & scale economies, contributing to the first delay. In response, Boeing consolidated its fastener procurement, directly negotiated with suppliers, for favorable pricing	*I care more about the prices than the delays of the fasteners*	If Boeing cared more about the delays than the prices, it should have encouraged the fastener suppliers to reduce lead time by making a better volume and/or price commitment, rather than discouraged them by squeezing them more on price.
Boeing selected Vought who had no engineering department to develop the world's 1st all-composite aft-fuselage.	*I need someone to share the cost and risk more than getting the project done on-time*	Had Boeing not known Vought's engineering capability (as a long collaborator) and the damage of using a firm with limited technical capability? Negative, but the need of risk sharing dictates.
"We underestimated how long it takes to do someone else's work" – slow progress at FAL to fix the traveled work.	• *We estimated delays, but underestimated them.* • *We don't have to hurry up to save someone else' money*	Boeing was expecting delays but nothing so bad. Why should Boeing work hard to catch up the schedule so that the suppliers can reap the most benefit?[2]
Embarrassing wrongly installed fasteners – poorly written doc. by Boeing Engr. misled its workforce	*I don't care much to manage it well*	If Boeing were more committed, such low-level mistakes should have been avoided.

Exhibit 13: The truth behind scenes for Boeing.

The reconciliation demonstrates that Boeing was really just concerned about its own cost and risk rather than the delays of the 787 program.

These irrational behaviors (that led to a majority of the 787 delays) are detrimental to the 787 program, but they can be rational to each individual firm, because what is the best for the program isn't the same as what is the best for each firm. What happened is that each firm tried to delay behind the schedule or passed its unfinished work to others because by doing so, it can save its direct costs, and have the damage, the extra indirect cost incurred by the delay, shared by other firms (i.e., the moral hazard issue).

[2] If Boeing works slowly, it barely incurs any additional cost at that time because the customers are loyal and the damage of contract penalty has already been done (LN 1 is in such a bad shape, there is little hope to get it done within 12 months, and Boeing only has to pay contract penalty for the first 12 months (Wellsfargo 2009)). If Boeing makes a significant effort to catch up with the schedule, the suppliers will reap the most of the benefit because at that time, the suppliers were paying for a majority of the development operations.

Thus, knowing the "irrational" behaviors were wrong for the project, Boeing and its suppliers still did it because it was in their best interests; that is why the delays were inevitable.

6. The Solution: Could It Have Been Avoided?

How could we avoid similar disasters in the future? Clearly it is impossible for Boeing and other large aerospace manufacturers to return to the "one-firm-does-all" model due to the absolute necessity of market expansion worldwide. Thus, the right question is perhaps on how to align the incentives in joint development projects?

6.1. Controllable vs. Uncontrollable Delays

A frequently raised question for the Dreamliner program is why Boeing did not penalize its partners for their delays? To answer this question, we must understand that there are two types of risk in development projects: the risk of uncontrollable delays and the risk of controllable delays.

The uncontrollable delays	**The controllable delays**
• Technical challenges • Natural disasters • Union strikes	• Careless lapse • Errors due to mismanagement • Firm's strategic behaviors
Unpredictable and unavoidable	Predictable & avoidable by extra effort & commitment

Exhibit 14: The types of delay risk.

Boeing did not penalize the suppliers for their delays because Boeing doesn't like to pay penalty to the suppliers for its own delays! This is the essence of the risk-sharing partnership: if the delay is caused by unpredictable and unavoidable events such as natural disasters and unexpected technical challenges (the uncontrollable delays), no individual firm should be held responsible. In fact, sharing the risk of such delays is fair because it allows the firms to avoid a completion devotion to one project and to spread the risk among multiple projects to achieve the portfolio effect, much like investment diversification in financial markets.

The risk sharing partnership, however, does not distinguish the types of risk but also force the firms to share the risk of controllable delays, which is not fair because a firm should not be held responsible for other firms' mistakes. More importantly, sharing the risk of controllable delays encourages such delays (due to the moral hazard issue) and thus leads to suboptimal project performance on both time and cost. Thus, neither penalizing nor sharing all types of delays is fair and effective.

6.2. The Fair Sharing Partnership

To better align the incentives of firms in joint development projects, we propose a new partnership, namely, "fair sharing", which allows the firms to share the risk of uncontrollable delays but assumes each firm the full responsibility for its own controllable delays. Specifically, upon a delay, the firms shall first identify its type. In case of an uncontrollable delay, the damage is shared in the same way as the risk sharing partnership. But in case of a controllable delay, the firm responsible shall pay not only for its own damage but also for the damages of other firms caused by the delay. In this way, the firms can share the risk of uncontrollable delays and achieve the portfolio effect; meanwhile, they can also eliminate the moral hazard issue and align their interests with that of the project.

I must point out that the fair sharing partnership isn't a panacea as its effectiveness relies on the firms' capability to distinguish the types of risk, which is not always easy especially in projects involving creative activities and substantial technical challenges. When such a project is delayed, it can be hard or impossible to tell whether the firms involved haven't tried their best or they tried but failed. Fortunately, the fair sharing partnership applies to complex projects with minor or moderate technical advances, such as extension, upgrading, or new combinations of existing technologies. These projects represent a vast majority of the development programs in the Aerospace and Defense industry.

6.3. How Could It Have Been Avoided?

We now discuss how some of the delays could have been avoided in the Dreamliner program by contrasting what Boeing did to what Boeing should have done (see Exhibit 15).

What Boeing did	What Boeing should have done
Share both types of risk (the risk sharing partnership)	• Distinguish between controllable and uncontrollable delays in contracts • Specify upfront which type of risk to or not to share (the fair sharing partnership)
After the delays occurred, Boeing had to assist/support the suppliers to • Keep them afloat upon Boeing's delays • Keep them afloat upon other suppliers' delays • Keep them afloat upon their own delays	• Have suppliers fully responsible for their controllable delays • Fully responsible for its own controllable delays • Share the damage of the uncontrollable delays

Exhibit 15: What Boeing did vs. what Boeing should have done.

Had Boeing utilized the fair sharing partnership, the first four delays could have been avoided or at least mitigated because both Boeing and the suppliers would have taken a much greater responsibility for their delays and thus been much more committed than they were under the risk-sharing partnership. That being said, there may still be delays, like the last three, but mostly due to unforeseeable technical challenges.

On the implementation side, because the fair-sharing partnership requires a much greater responsibility than the risk-sharing partnership, some suppliers may be reluctant to sign on. If Boeing must use a supplier even if it declines the responsibility, then knowing the supplier's financial incentives, Boeing should closely control and monitor the supplier to prevent potential "irrational" behaviors.

In reality, Boeing fought the delays by first tightening its control of the suppliers (tiers 1, 2, and 3) around the globe (Exostar 2007). Boeing built a high-tech operations center in a factory in 2008 to monitor the suppliers in real time to ensure that the 787 components and modules are tested right away at the original manufacturers before shipped out to the next level of integration (Xu and Zhao 2010). Second, Boeing acquired Vought's interest in Global Aeronautica in June 2008, and bought Vought's 787 operations in South Carolina entirely in July 2009. After these acquisitions, Boeing's share of the delay damages increased considerably, and it tightened up its internal control. Consequently, there are no more embarrassing mistakes since then, and the last three major delays are largely due to unexpected technical issues.

7. Conclusion

Boeing's experience in the 787 program provides a live example of how gaming behaviors in collaborative innovation can bring a disaster to the development of a promising new product. The root cause for the disaster was found to be the wrong risk shared by Boeing and its suppliers which give these firms a wrong motivation. Specifically, sharing the risk of controllable delays encouraged such delays because neither the suppliers nor Boeing was fully responsible for their delays, so all firms tend to slow down their work and put in less effort than what is right for the project. Together with a poor monitoring and control of the suppliers, the 787 slips are inevitable.

An important lesson learnt from Boeing's experience is that distinguishing various types of risks in innovation and sharing them selectively among partners are critical to success. Similar disasters can be avoided or mitigated by a better designed relationship, such as the fair sharing partnership, which allows the firms to share the risk of uncontrollable delays but assumes each firm the full responsibility for its own controllable delays. Combining this new relationship with a closer control and monitoring of the suppliers, innovation by collaborative is much more likely to succeed.

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