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Abstract

The Boeing 787 Dreamliner aircraft is a revolutionary step forward in passenger aircraft design and production. Boeing developed several innovations that make this aircraft more fuel efficient for the airlines and more comfortable for the passengers. Identified significant innovations include the composite material construction, fuel efficient and noise reducing engines, operational commonality with previous aircraft, improved aerodynamics, and a new approach to supply chain management. All of these innovations required Boeing and its suppliers to develop new technologies and set a new standard for passenger aircraft requirements. The most significant innovation, however, is the integration of these technologies in a single project. Unfortunately, Boeing failed to meet the original expectations for delivery, suffering multiple delays because of challenges associated with these innovations. Some of these innovations were so new, Boeing did not fully account for the complications that would arise. Despite a three year delay and numerous challenges, the 787 has advanced aircraft construction technology into the 21st century and proven Boeing to be an innovative industry leader.

History of the B787 Dreamliner:

The Boeing Company was founded by William Boeing in Seattle, Washington in 1916 and was originally called the Pacific Aero Products Company. In 1917, the name of the company was changed to The Boeing Airplane Company. Boeing merged with McDonnell Douglas in 1997 and is today recognized as an aerospace leader. Now Boeing is known to be the largest manufacturer of commercial jetliners and defense, space and security systems in the entire world. The company moved their corporate headquarters from Seattle to Chicago, Illinois in 2001.

In the early 2000s, Boeing was considering two concepts for a new commercial airplane. The first was the B747x to replace the B747-400 which was developed in 1985. The second was the “Sonic Cruiser” to replace the B767 series which were developed by 2000. In particular, the concept of Sonic Cruiser was to develop and aircraft that would be 15% faster than a typical B767 with same amount of fuel consumption. However, in 2001, in response to increasing oil prices, Boeing had to look for more economical alternatives. Airbus, a prime competitor of Boeing in the commercial airplane industry and was developing a supersized airplane, the A380, which was to be bigger than B747 (one of the largest passenger airplanes). The Airbus A380 was Airbus’ solution to high oil prices and maximizing efficiency. In turn, Boeing canceled one of the former concepts, the Sonic Cruiser project, and worked out a new plan, the B7E7. The B7E7 was later renamed the B787 Dreamliner.

In addition, there was an increasing shift in air travel philosophy from the hub and spoke transportation network to a point to point transportation system. According to aviation experts, the longer range the aircraft is capable of, the better it will allow carriers to introduce more point-to-point routes, so the passengers will have more options and fewer layovers ([1], [2]). Obviously, point-to-point travel is something of value to passengers. Part of Boeing's strategy with the new 787 is that the smaller 787s will complement routes flown by 777s, opening up more city pairs at greater distances than current medium sized, twin-aisle jets can fly [3]. This would allow airlines to develop new routes and increase frequency on existing routes as well as provide an overall increase in both passenger and cargo capacity [4].

The design of the older 777 was a technological breakthrough. The design process used concurrent product definition in the early stages, focusing primarily on design and manufacturing integration—meaning engineers designed a product that's economical to both purpose of manufacturing and operation. The 787 program capitalized on concurrent product definition as well, using advanced tools to design the aircraft. Streamlined design also meant simplicity in aircraft systems. The 787 was designed so that systems on the aircraft can be upgraded as technologies advance. As an example, the planned single advanced auxiliary power unit that will supply electrical power to certain airplane systems could be replaced with a fuel cell as fuel-cell technology emerges [4].

Needing a commercial success, Boeing decided to push the envelope with the development of the B787 aircraft. They decided to take bold steps forward in innovation throughout the entire design of the aircraft. These would be an advantage to Boeing, moving from an aircraft producer to more of an integrator. Most of the aircraft would be built in plants around the world and then assembled at the Boeing facility in only three days [5]. These innovations would also have a number of features making the aircraft more attractive to airlines than any previous aircraft.

Boeing said the aircraft will be quieter, produce less emissions, and use 20% less fuel than comparable planes while giving passengers a more comfortable ride, better air quality, and larger windows. Boeing stated that it was to be the company's most fuel-efficient airliner and the world's first major airliner to use composite materials for most of its construction. Some of its distinguishing features were to include a four-panel windshield, noise-reducing chevrons on its engine nacelles, and a smoother nose contour.

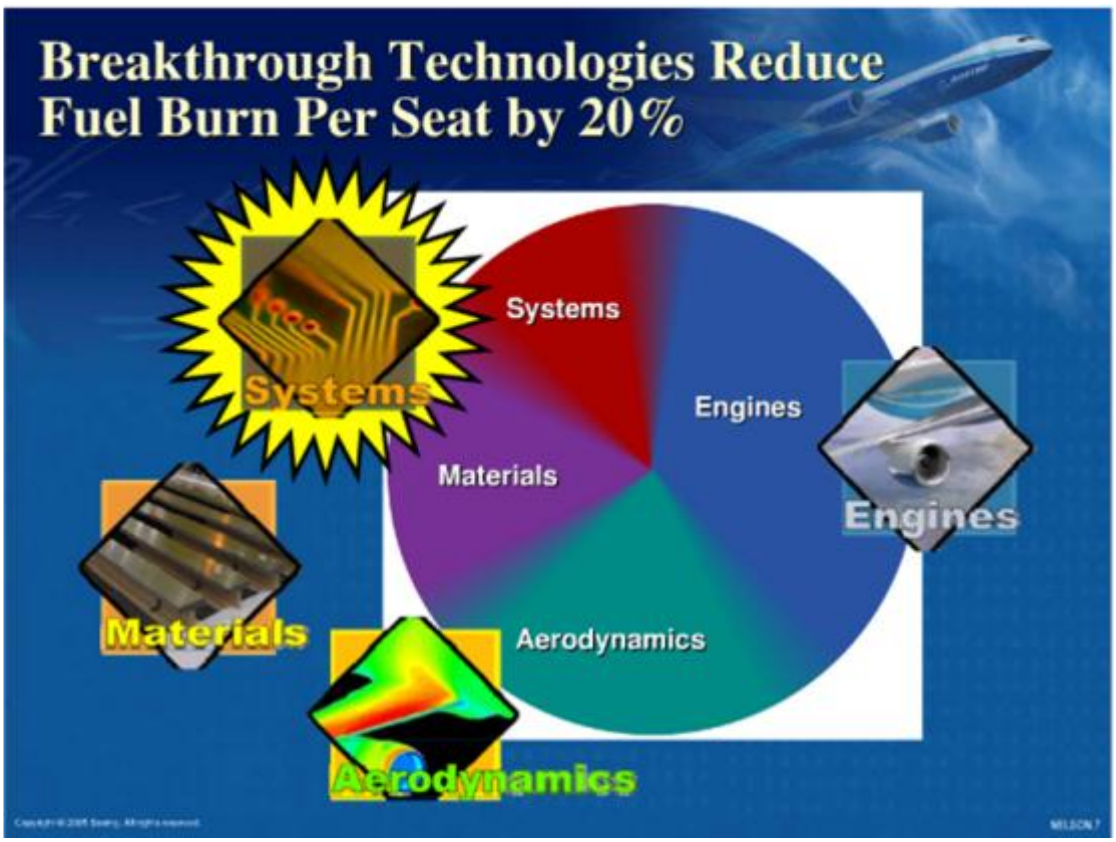

Figure 1. Breakthrough Technologies Reduce Fuel Burn Per Seat by 20%

The objective of this paper is to review the most significant innovations in the 787 and determine what challenges were involved in properly managing those innovations. It is our goal to understand what kinds of challenges arise with innovations and if there's a relation between the magnitude of the innovation and the challenges involved. In addition, we want to understand what Boeing did right and wrong with the project.

Composite Materials:

Arguably, one of Boeing's most significant innovations with the 787 aircraft was the use of composite materials for most of the structure. While the use of composites in aircraft wasn't radical in itself, it was the amount of composite materials and the move away from a traditional metal superstructure that made the 787 design unique. Though Boeing had experience with composite materials and its dimensional stability [5] in the 777 aircraft along with military applications in the Boeing V-22 Osprey and C-17 transport aircraft, it was the scale and scope of the usage in the 787 that was unprecedented.

Boeing used carbon fiber reinforced plastic (CFRP) as the composite material to compose the fuselage, wings, tail, doors, and interior. The completed aircraft is estimated to contain 35 tons of CFRP [6]. The 787 contains 50% composite materials by weight and 80% by volume [5]. See Figure 1 for the composition of the structure of the aircraft. The most radical feature of the 787 composite fuselage was the fact that each fuselage section was fabricated as a complete part; a 20 foot long by 18 foot diameter cylinder instead of simply placing composite panels over an interior frame. Windows, doors, and access hatches were then cut into each section to complete fabrication. Each section was then transported to a final assembly site to be joined with other sections as the aircraft completed construction.

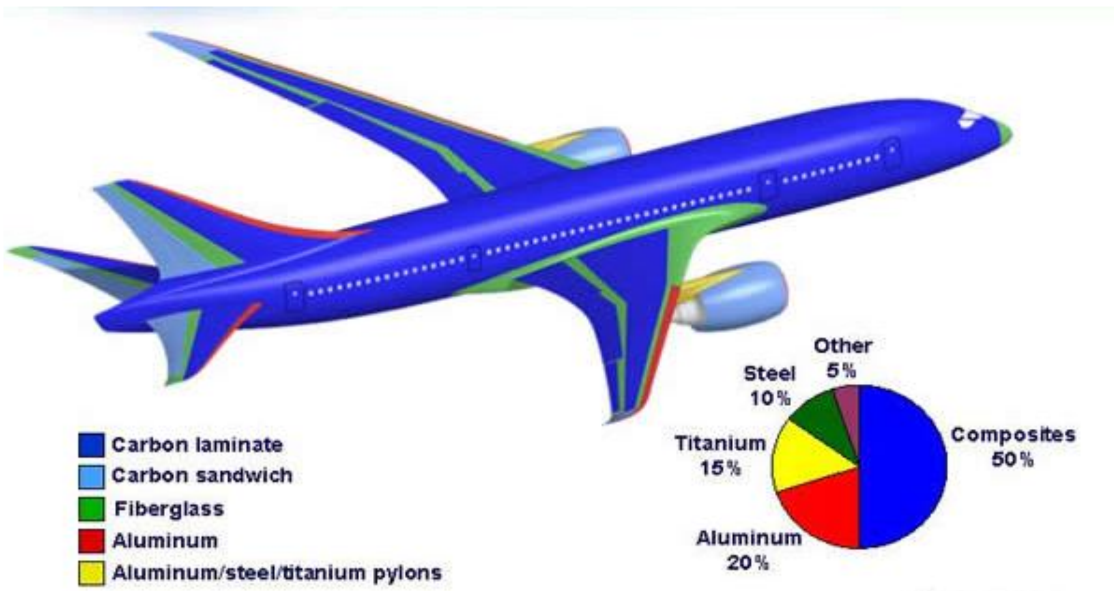

Figure 2. Composite Solutions Applied throughout the 787

There are several advantages to Boeing's innovative use of CFRP in the 787. These include:

- Reduced aircraft weight. The CRFP used in the Boeing aircraft was a weight reduction of 70% over steel and a reduction of 40% over titanium. Reducing the weight of the aircraft in turn, improves fuel efficiency and range of the aircraft.
- Fatigue resistance. Because CRFP doesn't fatigue like metal structures, it can withstand repeated cyclic loading better.
- Corrosion resistance. CRFP doesn't oxidize like metal and is less susceptible to structure-weakening corrosion.
- Enables enhanced passenger comfort. Because of the fatigue and corrosion resistance, the aircraft can withstand higher internal pressures and higher internal humidity that more closely replicate the environment on the ground. This enhances passenger comfort better than existing aircraft which are required to create lower-pressures and dryer air inside the passenger cabin.

Other aircraft require that dry air environment in order to prevent the moisture from building up on the interior surface and weakening the hull strength.

- Allows larger, more integrated structures & systems. Instead of attaching multiple smaller structures together, the composite sections are integrated to fit together in a smooth manner. Structural systems can be integrated with acoustic damping systems, or thermal transfer system [5]. Integrating larger structures reduces the total number of fasteners required for construction; instead of attaching each panel on the aircraft, only sections need to be joined

Figure 3. Fuselage Component

together. Removed a number of assembly steps because large sections were joined together instead of dozens of hundreds of smaller components [7]. The design and build process of the 787 added further efficiency improvements. Manufacturing a one-piece fuselage section eliminated 1,500 aluminum sheets and 40,000 – 50,000 fasteners [8].

- More future growth potential than metals. Composite materials have more future potential than metals, which have been used for decades. New technologies in composite materials are being developed and can have improved future applications [9].

All of these factors made the development of a CRFP composed aircraft a very attractive innovation to Boeing; however, the execution was somewhat more challenging. While Boeing had experience with CRFP in previous projects, the scope and scale of the composite structures on the 787 was unprecedented. There were a number of challenges associated with this innovation including material composition control, developing inspection and maintenance programs, and developing new tooling.

All CFRP materials were provided by Toray Industries, Japan. Toray is the world's largest producer of carbon fiber materials [5]. CFRP production at Toray skyrocketed due to the Boeing 787 project. Toray itself had to increase capacity to keep up with the project. Boeing consumed enough resources to drive CFRP costs and impact the CRFP supply for other buyers. Because of the high volume of CRFP order by Boeing, and the slow processing time of the composites, in order to keep up with the 787 project schedule, production had to improve. Toray had to meet with their suppliers to ensure the production technology could keep up. This increase in CFRP production was accomplished through new tooling and manufacturing processes. An advantage to Toray and its vendors is that the innovations and technology developed to increase this production was proprietary to them and could be used outside the Boeing project [5]. This marks the first time for Boeing to outsource the entire wing design and manufacturing to external suppliers: Japan's Fuji Heavy Industries is responsible for center wing box and installation of the wells; Mitsubishi Heavy Industries manufacturing the wing box; and the fixed section of the wings and the landing gear well.

While Toray produced the CRFP material, it was then spun into each fuselage and wing section at other facilities. The CRFP “tape” was spun around a mold in the shape of the final product and the baked to fuse together into one complete structure. Any contamination or air bubbles that are trapped in the shell during fabrication can lead to defects during baking and the entire cast part is lost. This has occurred on more than one occasion [10].

Another challenge of the CRFP innovation is inspection and maintenance of the aircraft. Because the composite material does not show cracks and fatigue, failure of the material could go unnoticed until catastrophic. Competitor Airbus was also using 50% composite materials, but created composite panels to go over a more traditional metal superstructure, which was perceived as a more conservative design. Reaction of the laminated composite materials could be compromised due to moisture expansion at altitude. Boeing has addressed these issues and launched the GoldCare program in response, along with developing new off-the-line inspection methods including x-ray inspection of each fuselage section for errors in the CFRP matrix. New coatings had to be developed to prevent delamination and crack propagation [5].

Production tooling for handling each section of the plane was another new challenge associated with the 787 project. Because each section was thermoset, large ovens had to be constructed that could house the large composite sections [5]. In order to maneuver each composite section, large holding fixtures and jigs had to be designed and constructed to position each composite section for further operational processing [5].

Though each of these challenges was met, they were met with varying degrees of success. The concurrent design process didn't allow time for unanticipated problems. For example, the wing joint on the plane did not behave as predicted in the virtual model. This required redesign on the fly of the joint at multiple locations [11]. Initial fuselage sections failed inspection when they arrived at Boeing [10]. This is due to errors in the fuselage fabrication process. Each composite section was a large piece and any defect in any section of the piece meant that the entire part needed to be replaced. Overall, the use of a composite structure appears to be successful for the project. While some project delays were associated with the composite processing, significant challenges associated with the composite structure were addressed and resolved.

Fuel Efficient Engines:

In the late 20th century and beginning of the 21st, people became increasingly conscious about environmental changes and protecting it against man-made pollution. As a result of such awareness, airlines became increasingly under fire for their contributions to carbon dioxide emissions and global warming. For this reason along with increasing fuel prices, Boeing integrated fuel efficient and eco-friendly technologies into the 787 [12]. Like the composite structure of the aircraft, fuel efficiency was perhaps one of the greatest innovations on the 787. To accomplish more fuel efficient and quieter propulsion innovation, Boeing considered the "more electric" power system architecture with bleedless engines and a directive to reduce total cost of ownership as critical design goals for the 787 power systems. These goals gave way to decisions in technology that brought engine efficiency and robustness to new highs.

To increase fuel efficiency, Boeing requisitioned Rolls-Royce's Trent 1000 Jet and General Electric's GEnx engines in the fuel efficiency innovation. For the first time in the history of commercial aviation, both engine types will have a standard interface with the aircraft; this will allow any 787 aircraft to be fitted with either a GE or Rolls-Royce engine at any point in time. Moreover, the 787 engines are interchangeable at the wing, thus providing airlines with the flexibility to change from one manufacturer to the other if the circumstances arise. Furthermore, it makes it easier to reconfigure or update the airplane when moving between fleets. These simplifications enable airlines to cut operating costs dramatically [13].

The Trent 1000 Jet's unique system which is used during take-offs extracts power for the 787's starter-generators from the three-spool engine's intermediate pressure shaft. It was argued that its arrangement improves the engine's fuel burn by about 6 percent compared to designs whose power extraction comes from the high-pressure shaft. This argument comes down to the fact that the intermediate pressure shaft's speed better matches the demands of the 787's starter generators, particularly during descents. Another innovation in the engine is that fact that Trent 1000 features titanium instead of steel containment case for weight savings and corrosion resistance. The engine's 20-blade fan system includes features such as a swept blade design with a lower hub-to-tip ratio than previous models. What was to be accomplished by the chosen fan design was to create a "big aerodynamic area in as small a volume as possible," which in turn leads to reductions in drag [14]. The design also contributes to a flat fuel burn profile, or consistent efficiency across different power levels.

Andy Greer, a chief engineer of the 787, noted: “Not all the improvements involve bits of metal and springy things”. He gave the example that Trent 1000 will go into service with more engine monitoring functionality than the company’s previous engines. The Trent 1000 has the usual complement of electronics and sensors related to this task as well as about ten additional sensors for pressures, temperatures, speeds and vibration that provide diagnostic and predictive maintenance data. This will make it easy to monitor engine health in addition to managing its performance on wing [14].

The GEnx engine is based on the company's GE90 engine but has some technology “firsts” in commercial aviation. It is more than 15 percent more fuel efficient than the CF6 engines with similar power. Part of that gain comes from a materials-related weight savings. GE engineers managed to cut the weight of the engine and related hardware by about 800 lb per aircraft. The company also optimized the aerodynamic design and combustion of its engine core. GE takes power from the high-pressure compressor of its two-spool GEnx engine for the 787.

With the GEnx, the company, for the first time, decided to go with a composite fan case, as well. The composite fan case is made from epoxy reinforced braided fabric from A&P Technology. The composite fan case is responsible for the bulk of the engine-related weight savings which is about 350 lb/engine. Some of the weight savings comes from the fact that these composite fan cases are strong enough to contain a suddenly-detached fan blade without the need for a kevlar wrapping that has been standard practice with aluminum fan cases. But as with the CFRP fuselage and superstructure, weight savings aren't the only thing composites bring to the table. They also have maintenance implications. “Composites get rid of the corrosion issue,” says Melvyn Heard, one of GE Aviation's general managers for the GEnx [14].

GE also implemented a combustor technology it has been maturing for the past decade. This Twin Annular Pre-Mixing Swirler (TAPS) system uses two swirlers adjacent to the fuel nozzles to pre-mix fuel and air prior to burning. The swirl creates a more homogeneous and leaner mix of fuel and air that burns at lower temperatures than in previous designs. One result is a significant reduction in NOx emissions. Heard estimates the GEnx engine has 50 percent lower NOx emissions than a comparable CF6 engine. Other types of emissions and particulate levels fall, too. TAPS may have a maintenance benefit, as well. “It creates a more uniform temperature profile, which is a friendlier environment for the engine components,” Heard states [15]. The GEnx also features aerodynamic optimizations throughout. Heard says GEnx has half the number of fan blades, at 18, than a CF6. This reduction, which helps improve noise levels, was made possible through optimization of the blade shape. In the high-pressure compressor, GE makes use of three blisks, which integrate the fan blade and disks into a single part. The integration saves both weight and maintenance costs. Finally, the GEnx engine is the company's first commercial engine to use counter-rotating spools as a way to minimize parts count and weight. Heard says that this design decision resulted in a 10 percent parts count reduction. GE went from a six- stage low pressure turbine to a seven-stage design on the GEnx “without any weight increase,” says Heard [16].

Using these engines, Boeing claimed the 787 would be near to 20% more fuel-efficient than the 767, with one-third of the efficiency gain from the engines, another third from aerodynamic improvements and the increased use of lighter-weight composite materials, and the final third from advanced systems [17]. This fuel efficiency allows airlines to save money and deploy the plane on longer routes. "On an aircraft of that size, even a slight reduction in fuel burn makes a big difference to overall cost," said Paul Sheridan, Head of Risk Advisory at Ascend. All Nippon Airways (ANA) predicts that the 787 will be able to travel 52% further than a metal-framed Boeing 767, whilst using far less fuel. Either way, it is a breakthrough in aircraft efficiency. A 20% fuel saving will represent a new benchmark for other designers to bear in mind and aim towards [18].

The challenges encountered in managing the fuel efficiency innovation was dealing with two powerful companies namely Rolls-Royce and General Electric who have proven success on their own to accomplish the innovation in fuel efficiency engines. Boeing 787 performance requirements pushed both Rolls Royce and GE to innovate without abandoning their proven technology frameworks [7].

Boeing suffered some setbacks in the original 787 delivery date due to the fact that Rolls Royce had to simplify the design of its power take-off system. The system at first included a relatively complex coupling between the high- and intermediate-pressure spools. It would lock the high pressure and intermediate pressure spools together during start-ups. Yet as Rolls engineers optimized the engine, they found they could meet all of Boeings start-up requirements without the coupling. So they got rid of it. “We just hook the generator to the intermediate pressure now,” Geer says. He estimates that eliminating the coupling saved about 100 lbs. of weight and more than 100 components.

Also, the Rolls-Royce engine failed during a test in early August, 2010. Rolls-Royce, based in Britain, acknowledged that the engine had suffered an “uncontained failure," in which a limited amount of debris spewed into the test facility. But Rolls-Royce said it could fix the problems, and it maintained that the failure was "unrelated" to its ability to make engines available for Boeing's flight tests [19].

GE agreed to modify engines on Boeing's 787 by the end of 2012 to stop fuel-vapor leaks, avoiding the possibility of further delays to the new plane. "GE Aviation is working a minor hardware change to the GEnx engine to eliminate the intermittent, limited fuel vapor emissions" by the end of 2012 and plans to retrofit engines by December 2014, Deborah Case, a GE spokeswoman, said in an e- mail [16].

Advances in engine technology were the biggest contributor to the 787's fuel efficiency improvements, Boeing says, with new GE and Rolls-Royce engines representing "nearly a two-generation jump" in technology for this sector of the airplane market [8].

The question of alternative power sources was raised during the design process, however, Boeing responded to this: "Our expectation is that fossil fuels will be around for some time. As the world's population grows and nations become more industrialized, obviously alternate power sources are going to be required. When the fuel cell technology becomes evolved, we can replace the jet engine in the back (APU) producing electricity with a fuel cell. That should not be in the too distant future. The 787 was targeted to be 20 percent more fuel efficient than anything out there flying today. The whole reason for the program was recognizing we needed to reduce fuel burn." Stated by the 787 Chief Project Engineer [8].

Operational Commonality:

The team designing the flight deck for the all-new 787 had two main objectives; first to introduce new technologies to help pilots and second to maintain significant operational commonality with the popular 777. They also had two main constraints; they had to meet stringent weight and cost targets. The first objective was relatively easily accomplished since it had been fifteen years since the original 777 cockpit design and numerous new technologies emerged that can help a smother and safer ride [7].

Maintaining operational commonality is also a key innovation objective for Boeing due to many advantages that come with it. The biggest ones are the cost savings that can be achieved as a result of generating scale with its operations. Commonality in manufacturing has long shown cost-saving benefits. It's at the heart of Lean manufacturing principles. Similarly having operational commonalities among planes also provides cost savings in terms of training costs for pilots as well as having the ability to schedule/deploy pilots into different planes that are operated similarly. The challenge for designing the new flight deck is introducing the newest technologies for helping pilots and continuing the existing operational commonality with 777. Boeing worked with a big number of pilots and industry experts while designing this innovation and the feedback that they gave to Boeing became the design requirements [20]. To achieve operational commonality with the 777, the 787 design team had to make sure the new airplane "felt" like a 777, which helped operators by reducing variability, simplifying operations and improving airplane reliability [20].

Airlines that fly both 777 and 787 models will benefit from proposed flight deck commonality between the airplanes. The 787 can serve both short- and long-range routes efficiently; the 787 and larger-capacity 777 teaming will simplify airlines' fleets, letting carriers match capacity with demand without affecting schedules or routes. This will generate significant cost savings for the airline industry. Also thanks to the airplanes' dramatically reduced fuel consumption carriers that operate the 777 and 787 will benefit from lower overall operating costs.

Commonality in design lowers design costs, can lead to a shorter design time, and results in less risk in the aircraft certification process. It also means better reliability and safety at launch. Passengers also stand to gain from commonality. With surveys showing that travelers prefer flying on the 777, the 787 is Boeing's most aggressive foray into designing an airplane that appeals to fliers. The 787's interior cabin design is blending the best ideas from the 777's signature interior with new innovations. As a result, passengers will appreciate features such as wider seats, wider aisles and larger overhead stowage bins. In addition, passengers will value the complementary safety goals of the 777 and 787 programs. All Boeing airplanes strive to meet the highest safety standards—not just as required by regulatory agencies, but to Boeing's even more stringent standards. The 777 has an excellent safety record, and 787 program's safety goals are the same as the 777’s [3]. Some other commonalities with 777 are nearly identical flight maneuvers, autoland and non-precision approaches and takeoff and landing technique.

The 787 features the industry's largest display screens, with five monitors that measure 15 inches on the diagonal. They provide more than twice the display space as the 777, giving pilots more information in easier-to-read formats and because the displays are a standard size found on laptop computers, instead of custom sizes as have been the case in the past, costs are reduced. The 787 flight deck also provides pilots with easy access to unprecedented amounts of information, and air transportation is safer than ever as a result [21].

Figure 4. Screens for 787

The financial benefits of commonality are particularly evident in the reduced training needed for current 777 pilots to be qualified as 787 pilots. It will take only five days of training, as compared to the 21 days needed for a pilot with no experience in a Boeing flight deck. The less time a pilot spends in training, the more time he or she is available for revenue-generating flights [20].

The biggest challenge in maintaining operational commonality was selecting which components of the 787 to enhance versus keep the same with other planes like the 777. This was a big challenge due to aggressive cost targets with the project. Any new additions will increase the incremental cost. In order to achieve this Boeing designers had to be very selective when they propose new enhancements. For example, although the team studied other control mechanisms including a side stick, the team's analysis found that the wheel-and-column arrangement performance is strong enough so to minimize cost they decided to stay with the current design.

New aerodynamic design –wing tips, nose of cockpit and nacelle

New aerodynamic designs have many advantages for Boeing 787. For Boeing Company, they have very high level of R&D department in aviation field. In Boeing 787 their innovation include aerodynamic in wing tips, and nacelle. First, Boeing made use of state-of-the-art 3-D aerodynamic analysis and design tools to provide advanced transonic wing design for improved speed and lift. Their high performance, but mechanically simplified high lift system produces high reliability and reduced maintenance cost. This new 3-D aerodynamic design also includes multi-disciplinary optimization for best combination of weight, drag and engine performance. The second new aerodynamic design is tightly integrated packaging of systems to reduce the size of aerodynamic fairings for reduced weight and drag. Third, advanced aerodynamic features validated through extensive wind tunnel test program at both high and low Reynolds number facilities (a kind of equipment that gives a measure of the ratio of inertial forces to viscous forces and consequently quantifies the relative importance of these two types of forces for given flow conditions.). Forth, Laminar flow of nacelles reduces the drag and resistance by air. Fifth, variable camber trailing edge is also used by reducing weight and drag [22].

The composite structure also allows for a higher aspect ratio (the square of the wing span divided by the wing area) of the 787 wing. This is advantageous because drag or friction from the air is inversely dependent on the aspect ratio; therefore a higher aspect ratio indicates reduced drag. The craft also makes use of raked wing tips, which is another structural feature that reduces drag. Furthermore, the 787 fairings- another structure on the wings- are smaller to improved wing efficiency and allow for a smoother air flow ([12], [13]).

"Aerodynamic was a much evolved technology before the 787. One of the things that allowed us to make improvements in aerodynamics was composites. Aerodynamic efficiency comes from high aspect ratio of wings. Making a wing out of carbon fiber we've been able to go to a higher aspect ratio wing. Our ability to model the airplane in three dimensions has allowed us to optimize the aerodynamics in ways we never have been able to do before. The wing tips are purposely designed so they not only sweep back, but have a slight upward curvature. That's part of the aerodynamics, but the overall curvature of the wing is not a lot different from today's airplanes" stated Tom Cogan, Chief Project Engineer [7].

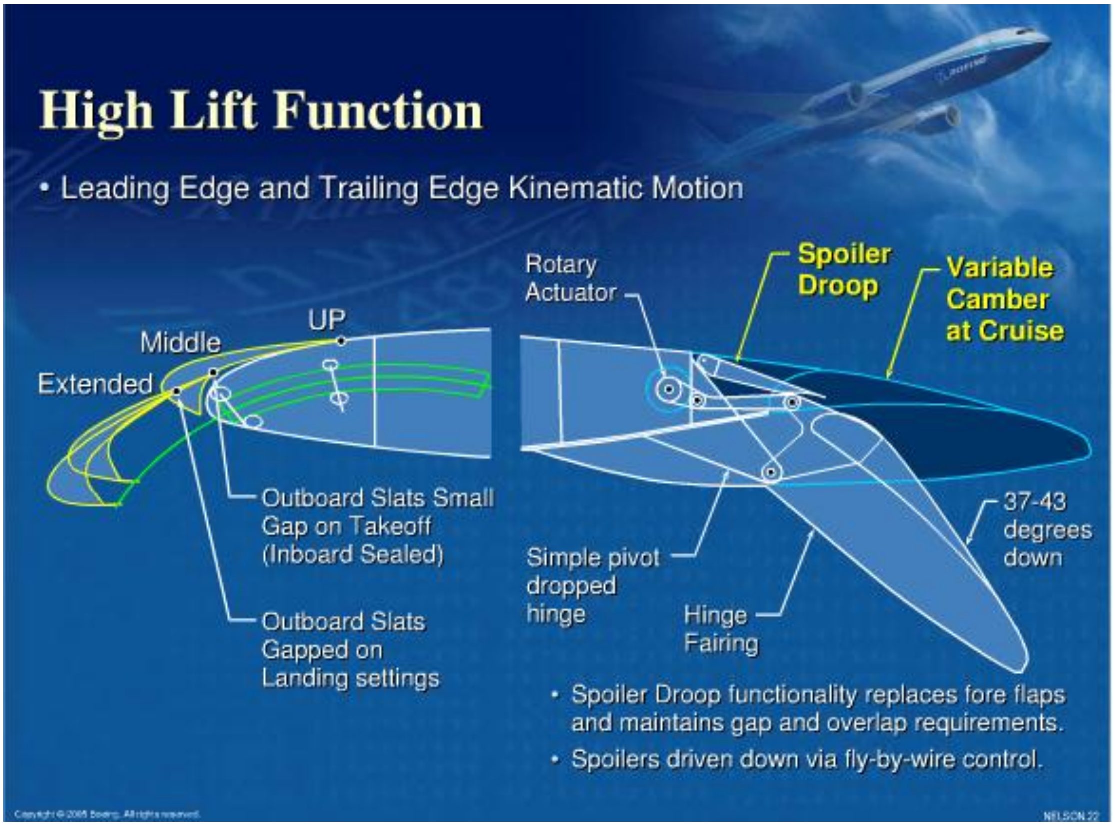

Figure 5. High Lift Function

From the outside, the most visible difference with the 787's engines is the nacelle. The trailing edge of the engine cover has a distinctive, serrated appearance. This design reduces noise by controlling how the fast moving air coming out of the jet engine interacts with the surrounding air. The design is so effective it allows a reduction in sound-insulation material from the airplane which in turn saves more weight [12]. For the airlines, a quieter airplane is a friendlier airplane for airport neighbors. This potentially means the 787 can fly into places other airliners are not allowed. Boeing says the noise footprint of the 787 will be 60 percent less than a similar size airliner, adding all noise louder than 85 decibels will be confined to within the airport boundaries.

In addition, Boeing plans to reduce airframe drag on the 787 by standardizing on a specific thickness of grey paint for the engine inlet which it says will preserve natural laminar flow over a larger area.

The benefits of laminar flow over the nacelle include increased range, improved fuel economy, and even reduced aircraft weight. These benefits add up to improve operating economics as well as reduced emissions. By using seamless paint layer applied according to tight Boeing design tolerances, as opposed to the more traditional airline practice of applying several layers of different paint, the company says thousands of liters of fuel will be saved every year [23].

The final nose configuration has many features. For example, in the head of the nose, it has four windows, and fewer posts. It provides pilots very wide view when they fly an airplane. All of the four windows are non-opening windows, so it will be more safety for the pilot. Another innovation technology is vertically stowed wipers and windshield washer. Those innovations improve the pilots' visibility.

Supply Chain Management:

Revolutionary innovation of the 787 project was not confined to its design technology but expended to its manufacturing technology. To reach its goal, reducing development cost and time, Boeing endeavored to change its supply chain management. The company decided to outsource over 70% of parts to national and international suppliers. Major components would then be assembled on the Everett campus in Washington and later in Charleston, South Carolina. Typically, Boeing had manufactured most parts for itself, or been supplied with parts from its plants. However, after successful collaboration with foreign suppliers like Japanese corporations in the former B777 project, Boeing gained confidence in outsourcing and expected continuous success. In fact, Boeing has done really well subcontracting over 50% of the parts to assemble their planes [24]. In the past, Boeing manufactured the big parts of their planes and contracted suppliers to make the small parts. Therefore, Boeing concluded expansion of outsourcing for the new project. Through outsourcing, Boeing wanted to share the risk and design burden with its suppliers or partners, and, instead, focus on the role of integrator [25]. Boeing thought of this idea because of lower labor costs in less developed countries to make small parts. In addition, such an arrangement spreads the cost and risk of the project throughout the supply chain and not exclusively on Boeing. In contrast, they didn't take into account that complicated parts must be manufactured in more developed countries were technology is more advanced and therefore labor costs are much higher [24]. Below is a graphic of the Tier 1 suppliers who manufactured the primary components of the 787 to later be assembled at the Everett campus [26].

While there is some loss if intellectual property for Boeing due to this manufacturing process, Boeing still retains ownership of the overall aircraft design and how to assembly and integrate the aircraft. Any supplier's proprietary technology is specific to their developed manufacturing processes; not the 787 itself.

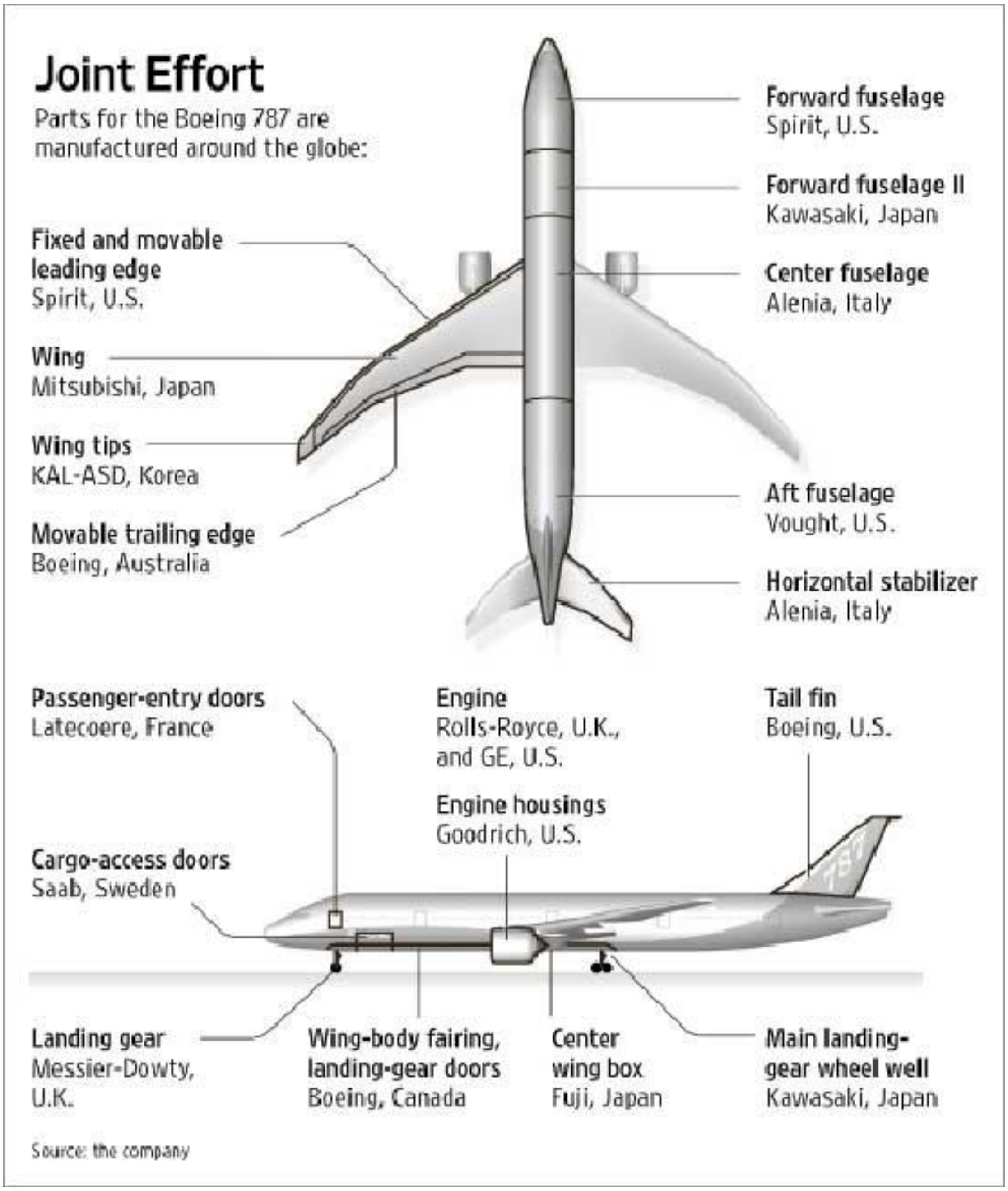

Figure 6. Join Effort

Currently, Boeing is working with more than fifty suppliers in 135 sites that are spread throughout the world. These different suppliers have been able to stay connected in the design process through virtual technology [8]. Yet it has been a challenge to keep everyone on track to deliver the 787 on schedule. The very first step of outsourcing was to establish digitalized infrastructure, known as the Global Collaboration Environment (GCE) for the collaborative work with its suppliers or partners of the 787 project [27]. Adopting a unified product lifecycle management (PLM) platform such as CATIA V5 (for design), DELMIA V5 (for manufacturing) and ENOVIA V5 (for collaboration) of Dassault Systems was part of that digital infrastructure.

Using integrated digital models has been common for design and manufacturing in airplane industries before the 787 project. However, in exchanging three dimensional (3D) models instead of classical blueprints for each part, compatibility for the product lifecycle management (PLM) is an important issue within a project. For example, in the A380 superjumbo project of Airbus, which is a strong competitor of Boeing, the most representative mistake which caused two year delay was from incompatibility among engineers in the Airbus. In detail, the mistake was that bundles of wires which transmit all of electric signals to control the airplane were designed shorter than the mechanical path they would follow. This error was found when the wire bundles were assembled on the practical assembly process. The cause of mismatched length of wire bundles was that, while the French engineers in the Airbus were using CATIA V5 which is the newest version of Dassault System's computer-aided design (CAD) software, the Germen engineers were using CATIA V4. There is an incompatibility issue like tolerance and unit conversions between both versions [28].

To avoid such mistakes, by extension, and to make efficient collaborative environment with its suppliers, Boeing made rules for making and using digitalized data, and encouraged its suppliers to follow the rules. First of all, Boeing adopted the unified version of PLM system and persuaded suppliers to use it. Carol Pitman, a director of engineering systems, and Kevin Fowler, the vice president of systems integration, had key roles to apply the unified all-digital design system on the 787 project [28]. They agreed to use Dassault's PLM platform, which had been used successfully in the former B777 project, for the 787 program. Boeing already had awareness of difficulties to exchange information between different CAD systems through its experiences before the Airbus' mistake. Duvall and Bartholomew reported that Boeing invested over a million dollars on purchasing software from Dassault. Boeing provided financial help to its suppliers to make them build same platform with itself. Additionally, the suppliers received the support and the tool to maintain the platform from Boeing for free [28]. By doing this, Boeing was able to share the information of the development project with related its engineers and partners without miscommunication.

The next step was to build a central data center to managing the information in Bellevue, Washington. In other words, this centralized management of data via Web, GCE, made Boeing's engineers and partners of all over the world connected virtually for all of design and engineering information regardless of time and location [29]. In particular, the partners were required to update all engineering and design data of their roles and progresses at least twice a week. While most of the suppliers and partners would be co-located around a Boeing plant for the design stage in the past, even foreign suppliers and partners were able to stay at their own locations and conduct collaboration with Boeing's engineers in the project. In addition, to support updates of each platform in all locations include partners and to ensuring software version control, Boeing utilized the data center. The reason of Boeing's centralized version control for each platform throughout the world was also to prevent miscommunication from unmatched data between different versions. Therefore Boeing provided all version updates to all related platforms four times a year regularly. With such impressive virtually connected Web infrastructure, Boeing gave confidence about success of the 787 project to its employees, partners and customers by demonstrating a successful example that a wrong design at early stage was modified intuitively on a large screen at "Virtual Rollout," in December, 2006 [30].

Nevertheless, though new methods were successfully set up in the manufacturing side, Boeing and its suppliers have suffered from many kinds of trial and errors because the company and subcontractors tried to do too many changes all at once. The results of the trial errors delayed the delivery schedule and took on additional costs. The first crisis came from the supply of fasteners because suppliers such as Alcoa were not able to secure enough supplies for early production demand [11]. After the incident with Alcoa, others delays occurred from various suppliers around the world. To add insult to injury, some virtual models were not fitted with practical parts in the assembly process. Scott Fancher, general manager of the 787 project, said, "We do testing for a reason. And that's because models aren't perfect" [11]. Therefore, the project members had to go back and find mistakes.

Several suppliers were implementing these new practices and it caused delays in the delivery schedule. Since all the parts had to be shipped on time to the Everett campus, even if one small part was delayed, this could freeze the entire assembly process. This scenario has occurred on more than one occasion [31].

Boeing also changed the manner in which they pay their suppliers. Instead of paying each Tier 1 supplier after their service was completed, under the new contract with the 787 they decided to wait until every single one of them had completed their share. Consequently, as some of the suppliers had major delays in the delivery of their parts, some contractors were forced to wait for a long period of time before they could receive their payment. This unexpected and unusual situation triggered a lot of anger toward Boeing because some suppliers depended on that money to keep their business thriving [31].

Due to the fact that Boeing was using so many more suppliers than before and many were running out of funds, this only enhanced the delays in the 787 delivery schedule. For example, one of the companies that Boeing was forced to buy was Vought Aircraft Industries who made the fuselage components. Vought was in serious debt and Boeing wanted to take control over the company because there was some concern about Vought being able to perform the job of building the fuselage parts. Even though this was a very expensive move, it was beneficial for Boeing to have control over the process and reduce the outsourcing of parts which was causing tremendous delays. By taking over Vought Aircraft Industries, Boeing was able to accelerate the manufacturing process of the 787 [32]. The buying up of troubled suppliers happened on several occasions in the development of the 787.

Boeing Charleston of South Carolina is one of the largest plant sites in the United States that also assembles the 787, though it was out of controversy that the site was placed there. In September and October of 2008 the International Association of Machinists and Aerospace had a strike against The Boeing Company [33]. During the strike that lasted two months, over 27,000 machinists walked out on the job and delayed even further the debut of the 787 and added a huge expense to the company [34]. It was after this strike that Boeing relocated its second assembly site of the Boeing 787 to South Carolina which opened its doors in June of 2011. Though the strike caused delays to the project schedule, it did force Boeing to create a second final assembly plant. The second final assembly plan will actually be helpful in meeting delivery demands throughout the life of the product.

At the detail design process, some subcontractors seemed to have higher responsibilities than their abilities, and Boeing overestimated their capabilities. Therefore, there are some questions which Boeing selected subcontractors with proper criteria. However, though they are correcting these problems, if the new development process is stabilized, and unless new paradigm is occurred in the commercial airplane industry, the speed of commercial manufacturing is expected to be faster than typical ways.

Project Delays and Innovation:

Despite all these new technologies and radical supply chain system, it has been suggested that the single most significant innovation in the Boeing 787 Dreamliner is the integration of technologies [7]. This is the integration of the composite structure with the fuel efficient engines with the electrical control and layout system with the supply chain management. All these elements together were necessary to successfully complete the B787 project. The challenge of managing these innovations was significant and unprecedented in a commercial airliner project like this. Unfortunately, the management of those challenges was not as successful as Boeing, and their customers, had hoped. Since all the parts had to be shipped on time to the Everett campus, even if one small part was delayed, this could freeze the entire assembly process. This scenario has occurred on more than one occasion [31]. Boeing's goal was to assemble a complete aircraft from the delivered components in only three days, and being production with two aircraft a month. Eventually, Boeing plans to produce 10 aircraft a month [35].

The B787 originally planned to enter service in May 2008 however the project has suffered from multiple delays. Boeing announced official delays several times; each delay being three to six months from the previous schedule. The announcements began in September of 2007, and were periodic through 2008, when they finally had a schedule they were able to meet. Officially, delays were blamed on fastener shortages, incomplete software, supply chain management issues, failure to keep up with production (or "work travelled"), incorrect fastener installation, and a machinists strike. Finally, the airliner's maiden flight took place on December 15, 2009, and completed flight testing in mid-2011. The first model was delivered in late September 2011 and it entered commercial service on October 26, 2011 [36], three years behind the original plan.

Never before had Boeing outsourced large parts or used mostly composite materials in their design. This caused more challenges that Boeing didn't anticipate and ended up costing more money. Boeings expenses in the program are estimated in the billions [37]. Additionally, some small suppliers couldn't survive with the new contract mandating that they wouldn't get paid until all suppliers had completed their work. Therefore, Boeing ended up buying some small failing suppliers to accelerate the process and have more control of the development of the 787. Boeing has created an amazing new commercial airplane despite the challenges they have faced along the way, but the most important lesson to be learned in this process is to keep suppliers close to the assembly line in order to have more control over their project.

In hindsight Boeing management has admitted that it would have been better to keep the core technologies more under Boeing's management. George T. Haley, who is the director of the Centre for International Industry of Competitiveness at the University of New Haven stated the solution best when he said, "Boeing should have held all systems and suppliers close to their assembly lines to facilitate cooperation between suppliers and Boeing" [38]. By outsourcing most of the work packages to its external suppliers, it is speculated that Boeing might accelerate the speed of hollowing out its core technological competence.

Currently, Boeing has over 800 planes on order [39] and a large amount of inventory in queue. According to current production schedule estimates, it will take Boeing five seven years to produce all the planes they have orders for. This isn't unreasonable considering Boeing plans to continue producing the 787 for the next 20 years and estimate product life cycle sales will reach over 3,300 units [35]. Several planes are half completed and must undergo rework processes to match updated design specifications. The first six planes were heavy and did not meet the weight specification. The first plane is actually being decommissioned, having been used extensively for testing and rebuilt several times for engineering modifications to refine the design [40].

Conclusion:

While Boeing developed several technologically advanced innovations in how the 787 was designed, fabricated, and assembled, the most significant innovation was the integration of those components in a single project. The delays and resulting costs associated with the failure of the 787 project to meet initial expectations were associated with the integration of these innovations into a single product. We did not find the poor management of any single innovation led to the delays, but it was an accumulation of several smaller issues that delayed the project.

Boeing experienced multiple delays large losses in developing the 787 Dreamliner; releasing a product three years late and billions of dollars over budget. Boeing pushed technological innovation in every aspect of the design and construction of the 787. They may have leapt farther than they were capable and the definitive success of the 787 has yet to be determined; however, there is no doubt that the innovations in the 787 will become the standard for commercial airliners for decades to come and set Boeing as an industry leader.

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