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## Blended Wing Body Architecting and Design: Current Status and Future Prospects

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### Abstract

Fixed-wing aircraft are viewed as no longer satisfying our needs today. In the past ten years, fuel efficiency and noise reduction have become the two biggest challenges for aircraft manufacturers. The recognition spurred aerospace engineers and system architects to come up with the Blended Wing Body (BWB), a new design for next generation aircraft. In this paper, we discuss the development of BWB from the perspective of design challenges that system architects and engineers faced during the design process, the architecting heuristics employed, and the rationale for design decision. In addition, body material and shape selection procedures, flight simulation, design optimization, and the advantages of the resultant design are also addressed. Thereafter, we look down the line and discuss the evaluation of emergence technologies on BWB aircraft subsystems, and a model for evaluating technology upgrade.

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### 1. Introduction

In 1988, Dennis Bushnell, now chief scientist of NASA Langley Research Center, asked “Is there a renaissance for the long haul transport?” With this question, he planted the seeds of future air transportation. Not long thereafter, McDonnell Douglas, now part of the Boeing Company, initiated a landmark design study.<sup>1</sup> In 2001, Boeing

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initiated a program called the Blended Wing Body (BWB) program. The key advantage of BWB is that it minimally distinguishes between wing-fuselage and fuselage-tail, and has a more “centered” volume than a conventional aircraft. While this aircraft shape may not be appropriate (because of wasted space) for a small passenger aircraft it is ideally suited for an aircraft designed to carry a large number of passengers. A BWB type aircraft has several advantages over a traditional aircraft. These include, greater internal volume, aerodynamics and structural efficiency, noise reduction, and most important, significant improvement on cost-per-seat-mile<sup>1</sup>. The aim of this paper is to take a critical look at the architecture development process employed on two BWB projects, Boeing X48 and the Hyperion project. This paper is organized as follows. Section 2 presents the rationale for BWB. Section 3 presents specifics about the development of BWB. Section 4 presents the highlights of Boeing’s BWB program. Section 5 discusses the Hyperion Project. Section 6 presents a model for technology evaluation. Section 7 summarizes the development and current state of BWB aircraft and presents a work for the future.

## 2. Rationale for Blended Wing

It all began when NASA Langley Research Center funded a small study project at McDonnell Douglas to design an aircraft capable of carrying 800 passengers, with a 7000-n mile range at Mach 0.85 (subsonic). NASA’s aim was to develop a new composite structure that exploited advanced technology in the new design.<sup>1,2</sup>

There were two challenges that had to be overcome to pressurize a passenger cabin for large aircraft. First, according to square-cube law, the available surface area per passenger for emergency egress decreases with an increase in passenger count. Second, cabin pressure loads directly and strongly influence hoop tension. At that time, the design team “punted” on the second challenge by assuming that in the future it would become possible to build an efficient structure to deal with hoop stress. As a result, the passenger cabin problem became the top priority. The design team began by considering three canonical configurations (i.e., sphere, cylinder, disk), capable of carrying a 800 passengers load. They soon discovered that while the surface area of the sphere was the smallest, it wasn’t streamlined. On the other hand, the cylinder and the disk had equal surface areas, and were canonically streamlined. Not surprisingly, the spherical shape fell out of contention. After the addition of wings, control surfaces, and wings to both shapes (disk and cylinder), the design team soon discovered that the total difference of weighted area between disk and cylinder shapes was 14,300 ft<sup>3</sup> or, in other words, there was 33% reduction in area for the disk configuration. This shape eventually showed dramatic improvement in aerodynamic efficiency. As a result the BWB won the competition for the 800-passenger aircraft. The unique aspect of BWB is that the fuselage also acts as a wing, inlet for engines, and a place for control surfaces.<sup>1,2</sup>

The next step was to design an effective airfoil. The design team came up with LW102A airfoil which had a lift coefficient of 0.25, and speeds up to Mach 0.7. The design team used an inverse approach to design the airfoil. They started with requirements that could support desired performance, and then worked backwards to design the desired airfoil.<sup>1,2</sup>

Due to its shape and configuration, the BWB aircraft burned 27% lower fuel, had 15% lower takeoff weight, 12% lower empty operating weight, 27% lower total thrust, and 20% higher lift/drag ratio. Taken collectively, these characteristics resulted in a clear advantage for BWB over conventional aircraft.<sup>1,2</sup> The flight mechanics and control system also faced different challenges because of the tail-less configuration of BWB<sup>1</sup>. The BWB concept was good enough to satisfy customer requirements. Of course, the requirements are different for military and civil transportation, the basic concept remains the same. The key architecting tenet that applies here is: *Concept formulation is complete when the builder thinks the system can be built to the client’s satisfaction.*<sup>3,4</sup>

## 3. Blended Wing Body Development

In 1994, a joint program between NASA and McDonnell Douglas got underway. With McDonnell Douglas as the program manager, other prominent team members included NASA Langley Research Center, NASA John H. Glenn Research Center at Lewis Field, Stanford University, University of Southern California, University of Florida, and Clark-Atlanta University. The goal remained the same: design a passenger aircraft capable of carrying 800 passengers over a 7000-n mile distance. The key architecting tenet implied by this requirement is: *Extreme requirements should remain a challenge throughout system design, implementation and operation.*<sup>1,2,3,4</sup>

With these requirements and the lessons learned from previous generation Blended Wing body configurations, the design team came up with a trapezoidal wing for the newly designed aircraft. This configuration afforded the opportunity to increase wing span by being able to achieve lower cost on weight.<sup>1,2</sup>

Wind tunnel tests on early BWB model were conducted at NASA Langley Research Center in the National

Transonic Facility. These tests afforded the design team the opportunity to assess aircraft performance close to the Reynolds number, and obtain realistic results. The results from wind tunnel experiments and Computational Fluid Dynamics (CFD) predictions were found to be in close agreement. A key result from the wind tunnel test was the confirmation of CFD methods.<sup>1,2</sup>

Since the aircraft was quite large, various smaller models were built and tested in wind tunnels. The result of wind tunnel tests also confirmed the estimated maximum lift coefficient and power of the control system in stall condition.<sup>1,2</sup>

The flight mechanics of the second generation BWB was tested by constructing a 6% scaled flight control testbed. For this project, NASA contracted with Stanford University. The model aircraft had 17-ft wingspan with 120lb weight. It was powered by two 35-cm<sup>3</sup> two-stroke propelled engines. The model, built at an appropriate scale to match real BWB flight characteristics, was first tested in July 1997 at El Mirage Dry Lake in California. The flight test showed outstanding handling capabilities of BWB within the flight envelope.<sup>1,2,5</sup>

To improve propulsion efficiency, the design team came up with the idea of Boundary-Layer Ingestion (BLI). The University of Southern California (USC) and Stanford University conducted research on the viability of this concept. This research was supported by NASA. Results from USC's wind tunnel simulation were used at Stanford University to improve the theory of the engine inlet on BWB. Various CFD analyses were subsequently conducted to understand and improve the overall concept.<sup>1,2</sup>

The integration of engines was the next challenge. To make a final decision on engines, the design team considered twelve different combinations of factors with the goal of choosing the configuration that best satisfied design requirements.<sup>1,2</sup>

Since the structure of BWB is unique, the use of conventional aircraft material and structure for BWB was not viable. The biggest challenge was the development of a new "center body" structural concept capable of absorbing cabin pressures. This characteristic is unique for BWB<sup>1</sup>. This is because BWB aircraft are complex and highly integrated, and require complex trade-offs to be made. As a result, integration is extremely difficult for this kind of an aircraft. The key architecting principle that applies here is: *No complex system can be optimum to all parties concerned, nor all functions optimized*<sup>2,3,4,6</sup>

The BWB also offered environmental and safety advantages. In fact, some safety features were unique to BWB. For example, engine failure could not cause harm to the pressure vessel, fuel tanks, or systems. As noted earlier, the BWB has a relatively low acoustic signature. Since the engines are above center line, engine noise cannot reflect from the lower surface of the wing. Since the engines used in BWB burn less fuel per seat per mile, BWB had a distinct cost advantage over conventional aircraft.<sup>1</sup>

Pursuant to the studies on previous generation BWB aircraft, Boeing created a baseline for BWB-450. While most design requirements remained unchanged, Boeing added a couple of new requirements. Table 1 presents the total requirements. A key requirement not shown in this table is airport compatibility.<sup>1,2</sup>

Table 1 list of requirements for BWB 450<sup>1</sup>

Parameter	Value
<b>Payload</b>	468 Passenger + baggage, three-class arrangement
<b>Design range</b>	7750 n mile
<b>Crew</b>	Standard two –man crew
<b>Reserves</b>	International reserve fuel Fuel Equal to 5% of Block fuel 200 n mile diversion to alternate airport One-half hour hold at 1500 ft. at holding speed
<b>Constraints</b>	11,000-ft field length 140 –knots approach speed 2.7° segment climb gradient 300-ft/min excess power at top of climb

Based on the architecting consideration discussed above, the design team came up with the final draft for BWB passenger aircraft, the 450 baseline.<sup>1</sup>

Because of the unique characteristics of BWB, Boeing adopted a new, pragmatic and functional, multidisciplinary airplane design optimization code to optimize the shape and the configuration of BWB type aircraft.

This code subsequently evolved and became proprietary Boeing software that Boeing called WingMOD.<sup>1,2,7</sup>

Since the aerodynamics of BWB 450 baseline was highly dependent on WingMOD, the WingMOD technique/method can be viewed as a primary tool for BWB 450 development. For propulsion, several CFD techniques were used to find the optimal solution. And various types of engine modeling was done to test different characteristics.<sup>1,2</sup>

The other development perspective addressed the aircraft structure, which plays a key role in BWB design. The BWB structure comprises center body and outer wings. The structure of outer wings was rather straightforward to choose because it is similar to that of conventional aircraft. On the other hand, specifying the center body structure of BWB was difficult. As a result, several studies were done to illuminate the key issue and converge on the best option. The use of aluminum as a center body structure was not feasible because it would impose an unacceptable weight penalty. Thus, the use of composites was the only viable option. The primary tool used for structural analysis was the finite element method.<sup>1,2</sup>

There were several lessons learned along the way. The impetus for creating a new type of aircraft, other than the conventional wing-tube, was a great motivation to create BWB. While the primary figures of merit were takeoff load and fuel burn, BWB system design and concept development process revealed a few interesting facts. Specifically, BWB showed characteristics and offered unique opportunities that were neither expected nor planned. These included ease of manufacturing, ability to define a platform family for systematic evolution, reaching a higher Mach number without changing geometry, and exhibiting resilient response in the face of emergencies.<sup>1,2</sup>

#### **4. Boeing Blended Wing Body Program**

The Boeing BWB program is a joint program between NASA, Boeing, and Air Force Research Laboratory. The funding for the project was provided by Subsonic Fixed Wing Project of Aeronautics Research Mission Directorate's Fundamental Aeronautics program. Based on the agreement between all parties, NASA was responsible to provide facilities, equipment, and range assets for flight test and range and ground safety. Boeing was responsible for delivering X48B aircraft and ground station, and assuring flight safety, airworthiness and mission success.<sup>8</sup>

The program goal was defined by NASA as developing new ideas (concepts and technologies) to change the future of air transportation. Specifically, the main goal was to reduce noise and emissions, improve vehicle performance, and develop highly fuel-efficient air transportation. The main goal of X48B flight test program was to verify and validate the flight control system of X48B, and eventually BWB.<sup>8,9</sup>

The design approach of X48B consisted of using low cost equipment where possible, using normal industry practices for electronic equipment, and where necessary using aircraft specific equipment (radios, IMU). A companion goal was to save weight to meet dynamic scaling requirements to achieve best results.<sup>10</sup>

Under X48B, two models of BWB were built and tested. A small model (LSV-1) 12ft model was built to run wind tunnel tests. A large scale (LSV-2) model was constructed for actual flight tests. On July 20 2007, the very first flight test of X48B occurred at the NASA Dryden Flight Research Center (DFRC). The bulk of the simulation was done with MATLAB Simulink. Wind tunnel tests were conducted on the actual X48B (1:1 scale) in the Langley Research Center in Hampton, Virginia. The airplane that was built for the actual flight test was 8.5% scale of the actual airplane. A significant challenge for BWB, and especially for X48B (and the later model X48C), is pitch tumble. As the aircraft exceeds a certain Angle of Attack (pitch angle) threshold, the aircraft begins to tumble because of its configuration, and eventually crashes. To address this problem, the design team implemented Angle of Attack limiters, which were intended to reduce the risk associated with this eventuality. Thereafter, Boeing conducted six degree of freedom simulation runs, with NASA conducting real time simulation and flight tests.<sup>8</sup> As noted earlier, all flight tests were done at NASA DFRC and were supported by NASA DFRC's Western Aeronautical Test Range (WATR). The WATR provided the team with telemetry, optical tracking, range safety and communication facilities. The Remotely Operated Aircraft work area in Edwards Air Force Base was an irregularly-shaped, sterilized, controlled airspace from ground level to 10,000ft. Since, this area had sunny weather for much of the year, this decreased potential flight risk while improving flight safety. Additionally, the team was able to exploit the availability of multiple runways in the area for the different flight tests.<sup>8,9</sup>

The X48B flight test program consisted of three key phases. In each phase, the vehicle was tested with different configurations. Each test was designed to test the maximum capabilities of the vehicle. As the design team passed each phase, risk continued to increase because of the inability to cover all conditions and satisfy all objectives.

It is important to note that there are extensive flight test objectives, and for any flight test it may not be possible to run comprehensive tests for each objective. Thus, any successful flight test is considered to be one that

satisfies a subset of objectives that are deemed to be of high priority. To this end a systematic approach for flight tests is to start with a modest number of objectives and requirements that are considered high payoff.<sup>8,9</sup>

The results of the flight test showed that the overall performance of the aircraft was not only acceptable, but in fact good and consequently the flight tests were demand a success. From the results of X48B flight tests, the responsible team confirmed that the flight control system of the BWB was feasible. They validated the design using data acquired from wind tunnel and ground testing. One of the great lessons learned from X48B flight testing was that the correlation of Ground and Flight data was not easy to accomplish, if there was no central repository for wind tunnel, flight, CFD, and simulation data.<sup>10</sup>

It is important to note that since the goal of the program was proof of feasibility of the BWB, most requirements and design approaches for the vehicle came from prior studies.

## 5.The Hyperion Project

Today, within the aerospace community, there is a global, multi-company collaboration on BWB design. This complex global project, called the Hyperion project, is growing rapidly. It addresses the challenges associated with cultural differences, language barriers, and bureaucracy in a field where work is traditionally performed by small engineering teams. The project recognizes that increase in fuel consumption, air pollution, and noise are going to be the biggest concerns in the aerospace industry by 2030. Recognizing this trend, NASA challenged the aerospace industry to come up with solutions that help achieve fuel reduction and restrict aircraft noise pollution in the vicinity of airports. Educating the next generation of aerospace system engineers to effectively deal with these challenges is of paramount importance today, as current aerospace engineering studies tend to focus solely on engineering fundamentals, with minimal coverage, if at all, of system engineering, manufacturing, and project management.<sup>11,12</sup>

Another area that gets short shrift is communication, essential to developing interpersonal relationships, inspiring team members, handling conflicts, and managing diverse opinions. In global communications, team members are likely to not know each other personally, or have the opportunity to immediately clarify conflicts. Therefore, a clear set of requirements and creation of interface documents becomes extremely important. The Hyperion project has recognized the deficiency and made communication management a central tenet of the project. The Hyperion project encompasses two main thrusts: *global project management*, with participation of three teams from different continents; and the *teaching of systems engineering principles* in aeronautics. A key intent of the Hyperion project is to expose aerospace engineers to different philosophies and techniques practiced around the world as well as the influence of cultural factors.<sup>11,12</sup>

The architecture and design of an optimal BWB is concerned with the engineering analysis of highly coupled systems. The analysis encompasses both aerodynamic and structural analysis, flight mechanical design, mass properties management, and modern control system development. In the first (design) phase of the project, there are two main decision gates, a Preliminary Design Review (PDR) and a Critical Design Review (CDR). The second phase of the project encompasses manufacturing, integration, and test. Each component of the aircraft is to be manufactured, tested and integrated at system level and tested again to validate and verify compliances with project requirements.<sup>11,12</sup>

Since three different teams in three different continents worked on this project, configuration control of documents became critically important. Each team was required to update the configuration control document at the end of an eight-hour work day, and pass it on to the next team often in a different continent. The model was designed to allow “packing” three regular work days into 24 contiguous hours, thereby accelerating project development. Personal skills and program schedules were the main constraints for distribution of the Work Breakdown Structure (WBS). Since different parts of the vehicle were being manufactured in different countries, an interface that would enable successful assembly of the vehicle was essential. For instance, since the center body was fabricated in Germany, and the wings were manufactured in US (Colorado), the interface between these two parts needed to match. To achieve this objective, an Interface Dimension Template was constructed from Plexiglas and was sent to two manufacturers. An important lesson learned from Hyperion project was the Follow-the-Sun technique. A key aspect of this project was the global distribution of work. This technique allowed three universities to participate in this project, learn from each other, and exchange knowledge on a global scale.<sup>11,12,13</sup>

## 6.Creating a Model for Technology Evaluation

When building a traditional aircraft, the high level requirements of the system (aircraft) drive the design process of the aircraft subsystems. However, as the subsystems become more complex, their integration becomes an important concern because of interdependencies and interactions among the subsystems.<sup>14,15</sup>



Understanding and performing the trade-off between candidate architectures requires a model that illuminates all relevant interactions between the subsystems. Such a model can also be helpful when considering technology upgrade. To this end, it is essential to understand the extent to which the system under question would be affected by a change in technology. While systems engineers usually understand the potential improvement made possible by a particular technology, it is nearly impossible to foresee how the changes would propagate through different subsystems, and what other modification may be required as a result of the way change propagates<sup>14</sup>.

In every system engineering process, there are three main activities: requirement analysis, functional analysis, and design synthesis. An aircraft is an assembly of subsystems that are designed to perform certain functions. Therefore, each subsystem can be viewed as a small, integral part that contributes to achieving the aircraft's objectives.<sup>14</sup>

Decomposing the aircraft into its major subsystem is a key activity in the architecture development process. There are multiple ways to decompose a system (aircraft) into its constituent subsystems. For instance, one may decompose the aircraft and create its specification tree such that it can be related to the index of the Air Transport Association (ATA) specification. According to the ATA chapter, a subsystem can be described by different properties and can perform multiple functions that contribute to the higher-level functionality of the segment to which the subsystem belongs.<sup>14</sup>

The state of the subsystem can be conveniently characterized by two different attributes: *characteristic parameters or static attributes* (i.e., weight, volume) which are the outcome of the design of the subsystem and are adequate to describe the subsystem outside its operational environment; and *variable parameters*, which are attributes that can vary during operation.<sup>14</sup>

Interfaces are the means by which different subsystems communicate with each other. In Systems Modeling Language (SysML) notation, the parameter associated with the transfer of information between interfaces is called a flow. A flow can be an input when the subsystem is a client, or it can be an output when the subsystem is a supplier. A subsystem can be both a supplier of a flow and a client for another flow. Since flow is a quantity related to communication between two subsystems through interfaces, it can be classified as a variable parameter. The variable parameters, that are not part of the flow category, are called operational parameters.<sup>14,16</sup>

Customer requirements are specified and reside at the topmost level of the system architecture. The design process starts with these top level requirements and goes through a series of design phases, starting with conceptual design and concluding with detailed design. Each phase produces incrementally more specific requirements for the next design phase. Subsystem requirements usually specify its characteristic parameters, while the interface requirements are coupled with the operating conditions of the system. The subsystem that dictates the requirements is called the "master" in the flow, while the subsystem that is expected to meet those requirements is called the "servant".<sup>14,16</sup>

The implementation of the technology evaluation framework/model can be object-oriented. Object-oriented languages allow designers to create a virtual model of the system that conforms to reality. The framework for technology impact evaluation has three main components: a) "Subsystem Modeler," which allow designers to define and model both the subsystems as well as the overall system; b) "Subsystem Library," which stores subsystems in a central database, and c) "Virtual Simulator," which allows designers to load subsystems from the library, and assemble them. To evaluate the impact of a potential technology upgrade on the overall system, the designer can load the new characteristics into the newly changed subsystem. The next step is to simulate the system, assess its behavior and performance through the different phases of the mission. During simulation, the behavior of the interfaces is monitored with the Virtual Simulator, which verifies the satisfaction of the different requirements. The output of the simulation is a set of requirements that the system-level parameters are expected to satisfy.<sup>14,16</sup>

## 7. Summary

The concept of Blended Wing body started almost 25 years ago. The desire was to build a new type of aircraft that would allow the aircraft to carry more passengers. NASA, Boeing and McDonnell Douglas were the first contributors to this concept. Each major design and subsequent studies were funded by NASA. The goal was to push the boundaries of current technologies and to breathe new life into civil transportation. There were many individuals from different disciplines that contributed to the BWB design process. In retrospect, it is believed to be a key reason for the success of the X48B flight tests.<sup>1,2,8,9</sup> The key architecting principle that informed the design process was: *The probability of implementing new ideas depends on the number of people in the chain leading to their implementation and on the probability that each person understands and retransmits that idea.*<sup>3</sup> This was the case with the BWB

project. It had extremely well-qualified individuals with flight experience. Also, by its very nature, a BWB has unique challenges in that it is a highly integrated vehicle for which the design process is likely to encounter numerous challenges that requires complex technical and programmatic trade-offs. On the basis of studies reported in this paper, it should be quite evident that a spiral development approach was the preferred implementation model for BWB. Each iteration of the spiral comprises four steps: Requirements Setting, Analysis, Test and Implementation.

Next generation aircraft such as BWB will require new methods of manufacturing and management, such as those used in the Hyperion Project. As such, it is essential to give future systems architects and engineers proper tools to accomplish their objective. At the same time, technology evolution brings new perspectives to the design process. Therefore, it is imperative to develop tools that will allow us to fully understand the extent to which technology evolution is likely to change system/subsystems design as we pursue the development flexible and adaptable systems that exploit new and emerging technologies.<sup>13,17,18,19</sup>

And, finally, human system integration (HSI) plays a key role in current BWB vehicles because they are, in fact, Unmanned Aerial Vehicles (UAV) and due to their experimental nature. These vehicles require a Ground Control Station (GCS).<sup>8</sup> Since the pilot controls the vehicle remotely from the GCS, the station needs to be equipped with multiple monitors and indicators to keep the pilot fully informed about the vehicle's state and status. Situation awareness is critical for mission success (i.e. flight test) and overall performance of the vehicle.<sup>8</sup> However, by adding multiple monitors to increase pilot situation awareness can have an adverse effect on the pilot in the form of unacceptably high cognitive and monitoring load. Therefore, the key tradeoff is maximizing pilot situation awareness subject to cognitive workload and attentional constraints.<sup>20,21</sup> Research is needed in this area to maximize joint pilot-vehicle performance, especially when both the system and pilot have to adapt to disruptions<sup>17,22</sup>.

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