Modular Open Systems Assessment of the B-52 Program: A Case Study

Ebonika Williams
School of Systems and Enterprises
Stevens Institute of Technology
Hoboken, NJ 07030
ebonika@yahoo.com

Abstract - *The B-52 program was started in 1952 to meet the U.S. Air Force's need for a strategic bomber. The B-52 still operates today despite numerous attempts to replace the durable, yet aging fleet with other bomber designs. This paper assesses modularity and flexibility of the B-52 Stratofortress bomber aircraft and whether its open, flexible design is key to its longevity. The Open Systems Joint Task Force (OSJTF) provides guidelines to defense companies for assessing flexibility of a design submitted for acquisition. The Enabling Environment principle of the OSJTF MOSA (Modular Open Systems Approach) design assessment tool is used to rate the B-52 bomber. This paper focuses on the program's ability to adapt to changes to key interfaces, evolving requirements, and leveraging new technologies. The B-52 success is attributed in part to flexibility and adaptability as a weapon system and the environment that was created to facilitate that flexibility.*

Keywords: MOSA, modular design, open system, flexible design, B-52, adaptability.

1 Introduction

The design of open, flexible systems is an important attribute in the acquisition and development of military aircraft. Modularity is a prime strategy used to design flexible systems. When a product is "modularized", the elements of its design are split and assigned modules according to a formal architecture or plan. Modularization typically has three purposes [1]:

1) to make complexity manageable,
2) to enable parallel work, and
3) to accommodate future uncertainty.

The B-52 Stratofortress program began in 1952 to meet the US military's need for a new strategic bomber to replace the Convair B-36 fleet. The successful delivery of the B-52B in 1955 kicked off a history of over 50 years of continuous service and is the longest serving combat aircraft in the world. It is respected as one of the most effective and versatile aircraft ever designed. What is the key to this aircraft's success?

The B-52 Stratofortress acts as a case study to explore the concept of flexible system design. This paper determines if modularity and open flexible design contributed to the longevity and success of this aircraft. The B-52B is emphasized as the baseline design and its ability to adapt to changes to key interfaces, evolving requirements, and leveraging new technologies.

2 Modular, Open System Description and Attributes

A modular, open systems approach (MOSA) to system design produces a product that can meet requirements, while providing flexibility for affordable upgrades to incorporate technological maturity and reception to uncertainty. This approach is meant to optimize a system's response to change and create an adaptive environment for that change. To facilitate this environment a system can be partitioned into reusable modules with loose coupling between those modules, incorporate commonality and reuse of components, and maintain controlled, standardized interfaces [1].

MOSA is very important in the military acquisition community. In the present economy, military weapon operational demands have increased. Commercial technological advancement is very fast, making some Department of Defense (DoD) weapon program initiatives obsolete by the time a program reaches deployment. As the world evolves with new technology and growing foreign threats, it is imperative that the US Government encourages MOSA business and technical strategy [2]. This is the only way to deliver better, faster, and cheaper warfighter capabilities to protect the United States of America. The Defense Acquisition System DoDD 5000.1 states that, "Acquisition programs shall be managed through the application of a systems engineering approach that optimizes total system performance and minimizes total ownership costs. The modular, open-systems approach shall be employed, where feasible."

As a result, defense companies have met the DoD's challenge for MOSA design. These companies are re-arranging their architectures and employing Integrated Product and Process Development (IPPD) environments. The DoD has encouraged MOSA development with the use of the OSJTF. The Open Systems Joint Task Force (OSJTF) is a collective effort by the Department of Army, the Department of the Navy, the Department of the Air Force, and the Office of the Under Secretary of Defense (Acquisition and Technology) that enables program teams in the acquisition community to implement commercial interface standards to develop systems using modular design concepts.

The cost of not employing MOSA design is high in the aerospace industry. Defense companies will not be competitive with other companies without it, as they strive to create products for their government customer. DoD believes MOSA is an integral part of providing joint combat capability for next century warfare. In addition, without this design approach, we are at risk for designing systems at very high development time and cost that are vulnerable and unprepared for future uncertainty including technological, unpredictable environment, and emergent system behavior [3].

3 B-52 Stratofortress History and Overview

The B-52 has survived over 50 years of advancing weapon system development, enemy capability and evolving US military mission profiles and mission tactics. The B-52 would not have survived had the initial design not been good. Wayne Boyne, Assistant Director of the National Air and Space Museum comments [4]: "Had the original design not been so superior, the Air Force would have opted long ago for a new airframe."

Figure 1. Picture of the B52-H [5].

3.1 Initial Design

The B-52 was originally designed for use as a high-altitude, strategic bomber used for long-range strike missions against ground and sea targets like supply bases, factories and cities. The US Air Force was seeking to replace its Convair B-36 fleet with a faster, longer-range bomber built to carry nuclear weapons for Cold War era deterrence missions.

The Army Corps initiated a design competition in 1945 and Boeing was eventually awarded the preliminary design contract. Boeing had already built a good reputation based on the success of its B-17 and B-29 heavy bombers [6]. They initially envisioned the B-52 to be a turboprop, but in order to meet design requirements, Boeing substituted the turboprop with the maturing jet engine.

3.2 B-52 Variants

The B-52 is considered a combination of capability initiatives from its customer and lessons learned from the B-47 Stratojet [4]. Extensive structural material study and design were incorporated to meet engineering requirements. Thus, the B-52 family consists of a family of collective aircraft with similar appearance but with both major and minor differences in systems, equipment, and performance. Each of the production models is powered by eight engines, two engines in each of the four nacelles. Also, all of the nacelles are attached to the wings by swept forward pylons extending below the lower surface of the wing [4].

There are 8 variants to the B-52 (B-52A to B-52H) from 1954 to 1962. There are currently 94 B-52Hs that remain from the total 744 Stratofortresses built in the 1950s and 1960s. Unless otherwise noted, information in this Section was attained per references [6-9].

3.2.1 B-52B

The B-52B was the first variant to enter service with the US Air Force in 1955. This version became the first major production variant of the Stratofortress with 50 aircraft being built and will be used as the baseline B-52 design for the MOSA assessment in Section 4.

This variant hosts both bomber and reconnaissance capability. The added reconnaissance capability was accomplished with the addition of a general purpose capsule that could be equipped with photoreconnaissance or weather reconnaissance configurations. The B-52B housed an improved bombing-navigation system with the MA-6A, which replaced the K-system from B-52A [8]. The crew size was also extended from 6 members (2 pilots, 2 bombardier-navigators, 1 electronic countermeasure Operator, 1 tail-gunner) to 8 members (2 additional operators for reconnaissance).

The B-52B performance had advanced beyond its initial requirements. Table 1 compares the performance of the B-52B to the aircraft's initial requirements. The last B-52B aircraft flew in 2004.

Table 1. Initial Requirements vs. B-52B Performance.

	Initial Requirements [4,8]	**B-52B Performance** [6]
Capable Speed	450 mph	630 mph
Average Speed	300 mph	523 mph
Service Ceiling	40000 ft	47300 ft
Tactical Operation Altitude	35000 ft	19800 ft
Combat radius	5000 ft	3590 ft

3.3 Service Modifications

In order to sustain the program, there were a variety of modifications to the B-52 during its history. Some of the major modifications are described below.

Strategic Air Command initiated the first major modification, the Big Four program, which was incorporated on all B-52Hs and retrofitted on previous variants in 1960. The modifications include [5, 6, 8]:

1) All weather, low altitude flight capability. This included some structural modifications because a low level flight was estimated to accelerate structural fatigue by a factor of 8.
2) Ability to launch AGM-28 Hound Dog standoff missiles
3) Ability to launch ADM-20 Quail decoys – these missiles improved defense capability
4) An advanced electronic countermeasure suite (ECM)

These modifications were completed in 1963 at a cost of $313 million [5, 6, 8].

There were several Electronic Countermeasure (ECM) modifications implemented over the years to enhance the aircraft's penetration capabilities. The Phase II ECM modification was started on the B-52C thru B-52G aircraft in 1961 at a cost of $127.6 million [8].

In 1965, the Big Belly modification program increased the majority of B-52Ds bomb capacity at a cost of $30.6 million. This change was initiated to expand its traditional strategic nuclear strike role in South Vietnam. As a result the B-52D would carry 60,000 pounds of ordnance, increasing and varying its firepower capabilities [6].

Another modification program to improve low level operations was started in 1971 at $248.5 million dollars. This upgrade incorporated a new electro-optical viewing system (EVS) that integrated with the existing terrain avoidance radar on the B-52G and B-52H airplanes [2]. Also in this year, AGM-69 static random access memory (SRAM) nuclear missiles were added to the B-52G and B-52H models for $400 million dollars [5].

The ECM Phase VI program began in 1973 on the B-52G and B-52H aircraft at $362.5 million [2].

In Quick Start modification program, the B-52Gs and B-52H's were equipped with a cartridge start capability to enhance pre-launch survival. This $35 million retrofit program began in 1974 [8].

The satellite communications capability was added to B-52Gs and B-52Hs in 1979 for $108.7 million [8].

There have been more recent upgrades to the B-52. In 2002, the $108 million Avionics Midlife Improvement Program (AMI) started the upgrade of the B-52H offense avionics systems for new software packages. Current navigation systems were to become unsupportable so this project included rewriting the B-52H's computer software in Ada computer language (known to be a modular and easily adaptable language) [6]. Without this upgrade, future weapons would not be able to operate in the current B-52 as their platform. B-52 flight commander, Major Ed Bellem stated, "It is the biggest improvement to the B-52 in twelve to fifteen years. AMI is a critical modification; an essential upgrade needed to keep the B-52 airborne." As a result the mean time between extensive aircraft repairs has increased from 700 hours to 7500 hours [6].

The most recent pending upgrades include a $500 million project to improve the flow of data into the cockpit with network-centric technology [6].

4 B-52 Modular Open Systems Approach (MOSA) Analysis

4.1 OSTJF MOSA Assessment Overview

OSJTF has developed an assessment tool which includes a set of MOSA design indicators. The MOSA Program Assessment and Review Tool (PART) was designed for program managers or acquisition decision makers to be used as an assessment for MOSA design [2]. MOSA is an integrated technical and business strategy; therefore OSTJF has built a MOSA framework based on both of these strategies. The framework is detailed in [2]. OSTJF's MOSA framework is shown in Figure 1.

Figure 2. OSJTF's MOSA Framework [2].

OSJTF's MOSA Principles [2] include: 1) Establish Enabling Environment, 2) Employ Modular Design, 3) Designate Key Interfaces, 4) Use Open Standards, and 5) Certify Conformance.

The implementation of these principles will create systems at reduced lifecycle time and cost with uncertainty tolerant designs. This paper focuses on the first MOSA Principle:

1) Establish Enabling Environment

An Enabling Environment establishes supportive requirements, business strategies and technology strategies for the development of open systems. This includes configuration management process, and defining program requirements and performance specifications that allow open systems development instead of design specific solutions. MOSA implementation plans, responsibilities and policies should be in place, while executing market research on emerging technology, module design, and interface standards.

The B-52B is evaluated as the baseline design, while focusing on the B-52 as a weapon system. Subsequent program history is used as supporting evidence and the rationale for assessment scores. Only information attained per a public domain literary search is explored here. All reasonable assumptions are identified as such, along with areas where information was unavailable.

4.2 OSTJF MOSA PART Excerpt

Rationale and Supporting Evidence is given for each indicator score. The evidence is based on judgments drawn from the B-52 program's history and tangible illustration.

To what extent does the program's configuration management process encompass changes to key interfaces and corresponding standards?

- Degree of Implementation: Large Extent
- Rationale and Supporting Evidence: This indicator addresses the degree to which the program incorporates key interface designations, selected standards and design modifications in the change management process.

Note: The DoD first developed configuration management (CM) in the 1950s for technical management [10].

A great deal of information about the B-52's design modifications over the years is available in the public domain.

B-52B had some initial deficiencies with its bombing and fire control systems. Air Research and Development command insisted that the aircraft be "perfected" before delivery, however Strategic Air Command (SAC) objected to postponement of full scale production. The SAC Commander believed that "too many immediate improvements, refinements, or additional requirements could well be self defeating." At this stage, SAC protested against "unnecessary changes," believing that the units would benefit from "more standardization," and asked to participate in the coordination of all engineering change proposals [4]. This gave Boeing's customer initial control of change management with the intention of formalizing, governing, and closely inspecting the process.

After the B-52B was released for full scale production, the use of serial production provided for more timely improvements in aircraft without the expense of modifying an entire fleet. Serial production allowed the B-52 to take advantage of cutting edge technological advancements that would allow the fleet to meet and surpass its requirements, and expand its survivability. This greatly improved utility of the B-52 weapon system, allowing a punctual incorporation of new weapons and navigation capabilities. Engel and Browning explore the value of system upgrades and improvements for the lifecycle of a system in [11].

Traditionally, systems are designed to meet requirements at a certain point in time, without taking into account the fact that systems evolve due to [11]:

1) Market demand – desire by customer to increase product capability
2) Technology improvements – incorporate new technology
3) Maintenance costs that increase with age
4) Component obsolescence – redesign required as replacement components become obsolete

Figure 2 shows the lifetime value of a system with traditional design, versus the value of a system utilizing design for adaptability (DFA). Traditional design is not adaptable to upgrades and imposes design specific solutions on a system. Systems using DFA enjoy more frequent minor upgrades to minimize the value loss over the lifetime of the system, thus increasing the lifetime value of the design.

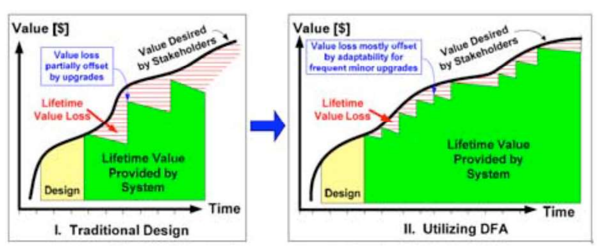

Figure 3. Lifetime value of a system, traditional vs. DFA [11].

Table 2 summarizes the major upgrades to the B-52 over the years. Variant releases were rapidly sequential and major modifications were frequent as well. Both are evidence of a DFA design.

Table 2. Timeline of B-52 Variant Releases and Major Modification Programs.

Variants	Start Year	Notable Modification Programs	Start Year
B-52A	1954	Big 4	1960
B-52B	1955	Phase II ECM	1961
B-52C	1956	Big Belly	1965
B-52D	1956	EVS	1971
B-52E	1957	SRAM	1971
B-52F	1958	Phase VI ECM	1973
B-52G	1959	Quick Start	1974
B-52H	1961	SatCOM	1979
		AMI	2002
		Network Centric	2005

The continuous release of variants and modifications suggests high level planning and control of the change management process for the B-52 lifecycle. These system upgrades increased the value and the life of the system by "closing emerging gaps between desires and capabilities" [11]. Upgrading the system is easier when a system is designed to accommodate these changes. The frequency of the B-52's upgrades suggests that the system was designed to facilitate these changes.

Successful demonstration of the B-52's ability to allow the system to evolve is demonstrated by its extended service life. The Air Force plans on continuing to use the B-52 until 2040, which is an unprecedented aircraft life span. Engineering analysis shows that the B-52's life span can endure beyond 2040. The airframe is limited to up to 35,700 flights hours [9]. At an average of 380 flight hours per year, the oldest B-52H could structurally survive until 2059. Its service life, however, is limited by the economic limit of the aircraft's wing surface flight hours. See the aircraft's service life in Figure 3.

This evidence supports a 'Large Extent' degree of implementation of the program's CM process supporting change.

To what extent is the system's architecture capable of adapting to evolving requirements and leveraging new technologies?

- Degree of Implementation: Large Extent
- Rationale and Supporting Evidence: This indicator assesses whether the system's architecture enables ease of change, mitigating technological obsolescence, and long life supportability.

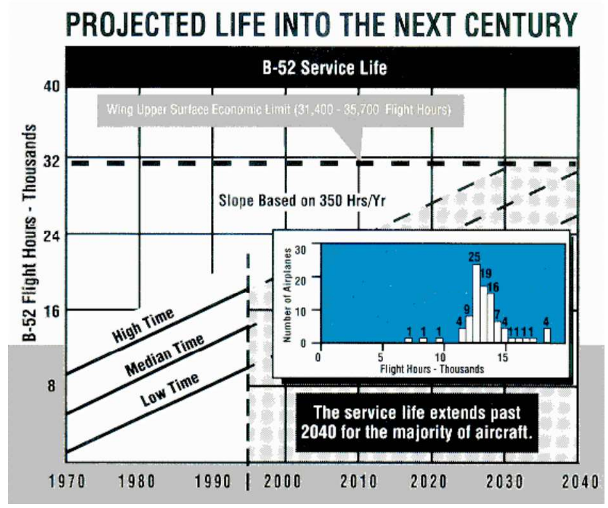

Figure 4. B-52 Service Life [9].

The B-52's continuing presence as a part of the US government's defense strategy lies in its ability to remain a viable weapon and military threat. The defense industry requires "uncertainty-tolerant" design. Reference [3] defines uncertainty as "the lack of complete knowledge of a particular system in the present or in the future." The main sources of uncertainty for the B-52 include:

1) Mission profile uncertainty- changes to national military strategy and the use of the B-52 due to political factors, and enemy technology and capabilities
2) Technological uncertainty- natural technology advancement

Each of these uncertainties are factors that contribute to the system's ability to change, mitigate technological obsolescence, and attain long life supportability. A system's ability to change and respond to uncertainty may be the single most important factor in overall system adaptability because it speaks to the system's ability to improve and react to changes in environment and requirements [11]. Table 3 is a summary of some of the unpredicted (uncertainty) issues and the B-52's response to that threat.

Much of the B-52 bomber's versatility as a weapon system can be found in the large number of weapons that the B-52 is able to house. The B-52 can carry 27 internal weapons, and as many as 51 smaller munitions and 30 larger munitions [9].

The aircraft's durable airframe and large capacity munitions environment allowed the weapon system to continue to evolve with technology. Smaller capacity subsystems were incorporated on later models of the B-52. This was used to minimize the pneumatic dependency from the early models and expand weapon capacity [4]. Later models took advantage of expanded avionics capabilities, which made the aircraft more adaptable to future bomb navigation and electronic defense equipment modifications. These changes improved overall subsystem performance and reliability, while expanding internal weapon carriage.

Table 3. B-52 Response to Future Uncertainty.

Uncertainty	B-52 response
Change from turboprop engine to evolving turbojet engine technology to meet initial customer requirements despite high fuel consumption	Design was originally built for a turboprop engine, however was able to be converted to a turbojet engine
Customer desires reconnaissance capability for enemy surveillance	General purpose capsule is incorporated into B-52B design for photo or weather reconnaissance
Customer desires low level flight capability to increase bomber penetration and survival due to increased range of Soviet surface-to-air missiles	Big Four modification program which included structural modifications and defense capabilities to endure low level flight
Nuclear superiority and intimidation military strategy of the 1950s	Improved ECM and defensive systems to the B-52
Flexible Response national security strategy of the 1960s	Big Belly, SRAM, Phase VI ECM, and EVS modification programs to increase bomber utility and capacity
Option-Oriented national security strategy of the 1970s	Extending weapon set to new technology long range air launched missiles, allowing the bomber to be a missile launch platform
Use of Satellite Communication	SatCOM capability added to bomber
Modular computer language design for current military platform	B-52Hs install Ada computer language

As the need for new missiles like SRAM and air launched control missiles (ALCM) arose, the B-52 was able to accommodate them. This indicates flexibility in the type of weapons that the bomber could support, or perhaps efforts by each weapon vendor to design for adaptability for the B-52. The latter would not have occurred without the DoD stating this as a requirement in the weapon design. This indicates the customer's commitment to the B-52 as an important part of US military forces.

5 Summary and Conclusion

The program achieved a high enabling environment score with its demonstration of continual use of serial production and upgrades to increase the value of the system, and tolerance for change and uncertainty. These characteristics contributed to the program's ability to leverage new technology.

It is reasonable to assume that technology mature modules (like that of the airframe) were distinguished from more volatile modules (like the weapon system). The maturity of airframe design contributed to the overall longevity of the aircraft, and its ability to support the volatile and diverse weapon system.

In the end, the importance of MOSA is best defined by its value. Quantitative evaluation of a system's adaptability metrics with math models (e.g., Black-Scholes) [3]; and analyzing historical aircraft bomber cost data, historical economical and technical advancement statistics, along with yearly obsolescence, maintenance, and wear-out cost can be used to determine value loss of system vs. value gained. Future study should include these methods.

It is reasonable to assume that the B-52's success is in part due to a modular open systems approach. The aircraft demonstrates value, longevity, and adaptability throughout its history.

The Air Force has kept the bomber in service because it has the highest mission capable rate (80%) when compared with the B-1 Lancer and B-2 Spirit bombers [12]. Also, the B-52 aircraft can carry twenty to thirty different weapon types, which is more than any other aircraft in the current US inventory [5].

The B-52 customer implies its worth with its support of over 50 years of US Military service. B-52 navigator and chief of avionics and weapons integration, Major Merrice Spencer, states, "The B-52 has proven its flexibility over fifty years, from dropping bombs at 50,000 feet to providing close-air support. The flexibility of this bomber will continue well into the future" [6].

Acknowledgment

The author acknowledges Dr. Roshanak Nilchiani, Assistant Professor of Systems Engineering and Engineering Management at the School of Systems and Enterprises, Stevens Institute of Technology.

References

[1] C.Y. Baldwin and K.B. Clark, "Modularity in the design of complex engineering systems," in A. Minai, D. Braha, Y. Bar Yam (eds.), *Complex engineered systems: Science meets technology*, Springer-Verlag, New York, 2006.

[2] Open Systems Joint Task Force, "A Modular open systems approach (MOSA) to acquisition," Version 2.0, Sept. 2004, http://www.acq.osd.mil/osjtf/.

[3] R. Nilchani and D.E. Hastings, "Measuring the value of flexibility in space systems: A six-element framework," *Systems Engineering*, Vol. 10, Issue 1, Wiley Periodicals, Inc., pp. 26-44, Dec. 2006.

[4] GlobalSecurity.org. "B-52 Stratofortress," http://www.globalsecurity.org/wmd/systems/b-52.htm.

[5] Wikipedia contributors, "B-52 Stratofortress," in *Wikipedia, The Free Encyclopedia*, http://en.wikipedia.org/wiki/B-52_Stratofortress.

[6] M.W. Bowman, *Stratofortress, The Story of the B-52*, Pen and Sword Aviation, Great Britain, 2005.

[7] B-52 Stratofortress Association, "The story of the Boeing B-52 Stratofortress," http://www.stratofortress.org/history.htm.

[8] A.T. Lloyd, *B-52 Stratofortress: In detail and design*, AirLife Publishing, Pennsylvania, PA, 1998.

[9] Federation of American Scientists, "B-52 Stratofortress," 2008, http://www.fas.org/nuke/guide/usa/bomber/b-52.htm.

[10] International Council on Systems Engineering, History, http://www.incose.org.

[11] A. Engel and T.R. Browning, "Designing systems for adaptability by means of architecture options", 16^{th} Annual International Symposium of INCOSE, Orlando, FL, 2006.

[12] J.R. Fox, "Consolidated List of Sources on Defense Acquisition, 1945–2003," Defense Acquisition History Project, Mar. 2004, www.history.army.mil/acquisition/research/section3.html.