ASME 2017 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference
IDETC 2017
August 6-9, 2017, Cleveland, Ohio

IDETC2017-67886

A CASE STUDY OF EVOLVABILITY AND EXCESS ON THE B-52 STRATOFORTRESS AND F/A-18 HORNET

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ABSTRACT

The moment a system is put into service it begins to lose value as technological and societal changes accrue while the system is frozen in the state it was constructed. System decision makers are faced with the choice of accepting a decline in performance, updating the design, or retiring the system. Each time a decision maker faces these alternatives, the value of the available options must be evaluated to determine the preferred course of action. A design that can adapt to changes with minimal cost should provide more value over a longer period than a system that is initially less costly, but less adaptable. This is especially desirable for systems that have large initial costs and/or a lengthy development cycle. The purpose of this paper is to evaluate the United States Air Force (USAF) B-52 Stratofortress and the United States Navy (USN) F/A-18 Hornet to characterize the changes in desired capabilities and what system attributes allowed them to either successfully adapt or prevented them from adapting. These observations allow the development of heuristics that designers can use during system design to enhance system lifetime value.

1.0 INTRODUCTION

Large scale Complex Engineered Systems (CES) are integral to modern life but are challenging to develop due to the complex interactions of numerous sub-systems, lengthy development time, extended in-service time, and potential for unanticipated emergent behavior [1]. Society benefits from these systems every time someone turns on a light with power from a nuclear power plant, travels internationally on a commercial airliner, or watches a movie transmitted from a satellite. Some of these systems provide capabilities that cannot be cost effectively obtained any other way.

The design effort and costs required to develop CES often leads to lengthy in-service periods. For example, the age of the average U. S. nuclear power reactor in 2009 was over thirty years. Many of these reactors had been licensed by the NRC to operate for 60 years, yet there is speculation that they ultimately could operate for eighty to one hundred years [2]. The total cost of building a replacement unit in 2009 was estimated at $7 billion per unit excluding transmission [3], which was a nontrivial fraction of the then $53.5 billion market cap for Duke Energy, the largest utility in the US [4].

A variety of methods for increasing CES lifecycle value have been explored in literature. Design for: adaptability [5], flexibility [6,7], changeability [8,9], and reconfigurability [10] all provide system designers with heuristics and tools to design an adaptable CES. The general focus of these studies has been on product architecture; with the optimization of system modularity and design of interfaces [11] as tools to reduce the time and cost, or generically “effort”, for modifying a system.

These approaches have generally not explored the capability of the system to support the components being modified or replaced. Upgraded or substantially changed components are likely to require system resources in quantities that differ from the original component. Even when no design change is required it is possible that the original component has become obsolete and unobtainable. This requires the qualification of a replacement [12] that might need different resources. This type of system attribute has been labeled “excess”, and research has begun to explore what excess is and what it’s properties are [13–16]. In this paper excess is defined as a modified version of that found in Allen [16] and Tackett [15] to be *the quantity of usable surplus of a system resource that is likely to be prohibitively expensive to increase with in-service design changes*. A prohibitive cost would be one for which the system decision maker would prefer performance degradation or retirement to configuration change.

This line of inquiry is important to CES design because it addresses one of the aspects of system design that may limit its lifetime. One example cited in literature is that of a nuclear powered aircraft carrier [16]. The electrical power generated by the carrier is a limiting factor for the addition or modification of

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systems. An upgrade requiring electrical power supply that is greater than remaining useable surplus will be far more likely to result in either degradation of system performance or the system's retirement. Conversely, the inclusion of too much capacity can result in unnecessary system cost or suboptimal performance [17].

Previous research on excess generally focuses on either non-complex systems or applies the proposed methodology to a complex system in the context of future or hypothetical changes to the system. Little work has been done to examine the evolutionary path that existing complex systems have taken in response to changes in their environment or desired capabilities. Knowledge, of what changes have occurred and what the changes were in response to, can help inform the design of both systems and the methodologies used in their development. Similar examinations of historical systems for lessons in design have successfully been conducted [18].

This paper contributes to the field by assessing the evolutionary trajectory of existing CES and what system attributes most affect that system's evolvability. Evolvability refers to a systems ability to *physically transform from one configuration to a more desirable configuration* [15] after being placed in service at a cost which isn't prohibitive.

The following section outlines the method by which the research and analysis was conducted to find appropriate CES and track their evolutionary trajectory in this paper. After the method, discussion of each system begins with the circumstances surrounding its design and desired initial capabilities. For the B-52, challenges to the system's operational capability are discussed and the compensatory design changes analyzed including the new/modified system capabilities and what physical or operational changes were required to support those capabilities. After the B-52 section, the F/A-18 has a more comprehensive developmental history and discussion of system evolutions with an examination of what symptoms were exhibited when excess was depleted. The paper concludes with a distillation of the lessons learned from the evolutionary trajectory of each system.

2.0 METHOD

This assessment qualitatively examines existing systems' abilities to meet unforeseen needs and identify what relationships exist between design excess decisions and in-service evolutionary capabilities. The systems chosen share characteristics associated with complex systems [1], have sufficient public information available to perform a qualitative analysis, and provide noteworthy examples of how a system's architecture impacts its evolvability.

A wide variety of systems were selected for preliminary study including commercial aircraft, military aircraft, space systems, nuclear power plants, and large infrastructure systems. To understand the why certain systems were changed it is critical for information to be available about the context of the environment in which the system operated. Records of the historical system context and accompanying system design changes are necessary to truly understand what challenges system designers faced when making decisions. The majority of selected systems had insufficient public information available to properly study evolutionary trajectory. The search was therefore limited to military aircraft due to the availability of historic records, government documents, and a plethora of accounts written by aviation enthusiasts.

The final two systems selected for study were the B-52 Stratofortress and the F/A-18 Hornet. The B-52 was selected because of its lengthy operational history and proven ability to adapt to technological challenges for 65 years, with another 20 planned. The F/A-18 was selected because it was unable to evolve to meet new operational requirements. A public debate between the U.S. Navy and the U.S. Government Accountability Office (GAO) provides public record of the design discussion which ultimately resulted in a redesign as the Super Hornet leaving only 15% commonality with the original airframe [19].

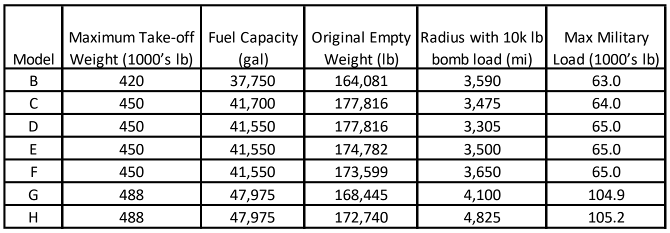
The research objectives were as follows. First, explore the environment in which the system was designed to capture assumptions and initial design decisions. Second, identify drivers of change for each system during its operations. Understanding what challenges drove certain adaptations, especially unforeseen challenges, could provide guidance for what to consider during initial design. Finally, identify and categorize the kinds of adaptations the systems experienced to overcome challenges with special attention payed to the types of components and the system resources required to support them.

These objectives provide knowledge useful to academics and system designers for military aerospace systems but also provide more general guidance for CES research and design. Since understanding the context in which each system operated is critical to understanding the motivation for design changes each adaptation described is preceded with the historical driver for that change. Each objective is explored in the following sections beginning with the B-52.

3.0 THE B-52

At the close of World War 2, and the opening of the Cold War, the United States found itself in need of a bomber that could deliver an atomic bomb to targets far from United States Air Force (USAF) bases. Initially only propeller aircraft like the B-36 could provide the desired range, but they were significantly slower than newer jet bombers like the B-47. Jet bombers were capable of faster speeds, but suffered from a smaller payload capacity and reduced range [20]. Between 1945 and 1948 the Air Force released increasingly challenging specifications for the new bomber and Boeing iterated through many different configurations. Finally, the USAF established requirements for a bomber with a range of 8,000 miles and a minimum cruising speed of 550 mph that could deliver an atomic bomb while flying above effective anti-aircraft gun range. In October of 1948 Boeing replaced the propellers on its proposed design with pairs of jet engines and the initial design of the B-52 was set.

The B-52 architecture has been leveraged in 8 different versions, designated with letters A-H. Figure 1 indicates how the design changed between generations by considering maximum take-off weight and fuel capacity [21–23]. This list does not include the A model as it underwent limited production and was primarily used for testing and evaluation. The final "H" model was fitted with new turbofan engines, extending the range to 4,825 miles with a 10,000lb bomb load. The discussion in this paper primarily focuses on the G and H models. The flexibility inherent in the B-52 architecture was already being demonstrated by the changes made over the 9-year production of the various models which included replacing the engines of the final variant.



Model	Maximum Take-off Weight (1000's lb)	Fuel Capacity (gal)	Original Empty Weight (lb)	Radius with 10k lb bomb load (mi)	Max Military Load (1000's lb)
B	420	37,750	164,081	3,590	63.0
C	450	41,700	177,816	3,475	64.0
D	450	41,550	177,816	3,305	65.0
E	450	41,550	174,782	3,500	65.0
F	450	41,550	173,599	3,650	65.0
G	488	47,975	168,445	4,100	104.9
H	488	47,975	172,740	4,825	105.2

Figure 1. A comparison of select attributes for B-52 models [21–23]

3.1 Changes and challenges to the B-52

Originally designed as a nuclear bomber before the advent of effective surface-to-air missiles (SAMs), the B-52 was subject to many changes to remain an effective military system. Adaptation to challenges often required multiple changes physically to the system and/or to its operational profile. Operational changes occasionally had unforeseen impacts on the system.

The adaptations described in the following sections are grouped by the specific driver for change. These drivers included: the development of accurate SAM's, the need to deliver conventional and precision guided payloads, and the integration modern communications equipment.

3.1.1 Surface to Air Missiles (SAMs)

The original conception of the B-52 used altitude and speed to shield itself from anti-aircraft batteries. The first challenge to the B-52 was the development of SAMs, which posed a credible threat to the fulfillment of its mission to deliver free-fall nuclear weapons [24]. Immediate changes to the bomber and its mission included three adaptations [22]:

1. change of mission flight path from high altitude to low altitude below enemy radar (300-500 ft.)
2. development of systems capable of defeating the tracking systems on the enemy missiles
3. development of stand-off weapons that alleviated the necessity for the bomber to penetrate as deeply into dangerous territory

Each adaptation required the B-52 to support the subsystems necessary to enable them and each is discussed in more detail.

SAM Adaptation: Change in Operational Altitude

The change in operating altitude required some modifications that were obvious to designers. Flying at low altitudes required the development of tools to avoid ground collisions and enhance bomb targeting. Many of these modifications were incorporated with the "Mod 1000" upgrade during which the aircraft were equipped to carry "improved bombing-navigation systems, Doppler radar, terrain avoidance radar, and low-altitude altimeters" [25]. Additional improvements were made in the intervening years to add multiple sensor and computer modifications that enhanced terrain following capability including the Electro-optical viewing system and the "Jolly Well" upgrade to the bomb and navigation system [22].

The unforeseen and then less understood phenomenon of fatigue failure also accompanied the transition to lower altitudes [23]. Increased turbulence at lower altitudes induced fatigue stresses on the airframe and resulted in two separate incidences of the vertical stabilizer failing mid-flight [21] and the appearance of wing cracking [24]. A modification program called "Hi-Stress" was implemented to provide structural modifications to support low-altitude flight. Modifications included: "strengthening the fuselage bulkheads, aileron bay area, boost pump access panels and wing foot splice plate, upper and lower wing panels, upper wing surface probe access doors, and the bottom portion of the fuselage bulkhead." [25] Later the "Pacer Plank" and ECP1050 programs further strengthened bomber airframes [22].

SAM Adaptation: Survivability Enhancements

The second adaptation to help increase survivability was the development of systems aimed at defeating the tracking system on enemy missiles. These modifications included decoy missiles, enhanced Electronic Counter Measure (ECM) systems, and other countermeasures.

The Quail missile was an air launched decoy designed to present a large radar cross-section and intense infrared signature [26]. The B-52 could to carry up to 8, but the typical load-out was for two. The architecture and strengthened airframe allowed the Quail to be carried on external hardpoints in addition to those carried internally.

The B-52 ECM systems were constantly upgraded as part of the race between enemy targeting systems and bomber defenses. Programs that enhanced ECM capability included "Mod 1000", "Rivet Ace", and "Rivet Rambler" which added a host of radars, false-target generators, jamming equipment and flare/chaff dispensers [22]. These were all fitted onto or within the space allowed by the airframe.

The efficacy of these systems was demonstrated in Operation Linebacker II during the Vietnam conflict. To maximize the protection offered by ECM systems the B-52s were organized into cells of three. On a bombing run that occurred the night of December 26th, 2 of 113 bombers were downed by SAMs and both were members of cells which were operating a plane down. In Operation Linebacker II B-52's supported by tactical, electronic warfare, and tanker aircraft flew 729 missions and

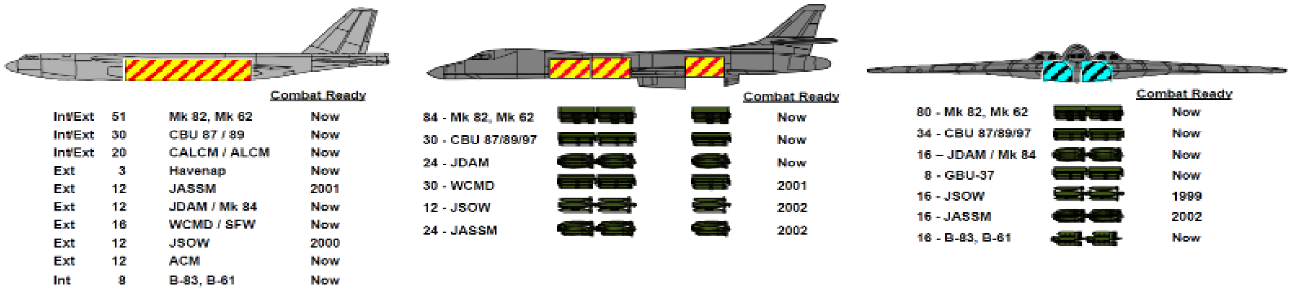


Figure 2. A comparison of modern US Bombers [27]

dodged more than 1,200 SAMs with fifteen lost bombers those lost often hadn't received the most recent ECM modifications [20].

SAM Adaptation: Standoff Weapons

As anti-aircraft weaponry improved it became clear that sending the B-52 into hostile airspace was an unacceptable risk. The development of better guidance technology for surface-to-ground missiles allowed for the possibility that a B-52 may never have to enter threatened space. Instead the bomber would carry weapons that would be deployed at a distance as to not endanger the bomber.

The first program was the development of the "Hound Dog" nuclear missiles that were designed to penetrate Russian defenses during the Cold War. Further improvement in missile technology led to the integration of the Short Range Attack Missile (SRAM) and the Air Launched Cruise Missile (ALCM) [25]. Each of these required supporting systems that were installed in the ECP2126 program that involved "the addition of modified wing pylons and launch gear as well as weapons bay rotary launchers and associated avionics equipment" [22] and the ALCM integration which included "new digitized offensive avionics systems" which allowed the B-52 to carry 20 AGM-86 ALCMs [25].

3.1.2 Conventional Weapons Modifications

The B-52 was originally designed in an era during which war planners believed that strategic bombers would primarily use nuclear weapons during conflicts. As history shows this was not to be the case and delivery of conventional weapons over to countries far from U.S. air bases was required for conflicts like Vietnam. The development of in-flight refueling changed the limiting attribute from range with a certain payload to how much weight and volume could be accommodated by the airframe.

The B-52 has been repeatedly modified to carry heavier and larger conventional weapons. The initial modifications involved the introduction of an external pylon on which weapons could be carried. This was first used to carry the Hound Dog nuclear missile, but was later adapted to carry SRAMs and ALCMs. With the introduction of the Heavy Stores Adapter Beams the pylons could carry additional weapons including those too long or large to fit the original I-beam [24]. The D model, primarily used in Vietnam, had its bomb bay modified to carry additional bombs internally on high density racks nicknamed the "Big Belly" modification increasing carrying capacity "for a maximum bomb load of about 60,000 pounds – 22,000 pounds more than the B-52F" [23].

The desire to reduce collateral damage while expending less ordinance to destroy a target led to the introduction of smart weapons. These weapons require that targeting information be conveyed to the weapon which meant both the targeting information had to be generated via positional system and communicated to the weapon. The conventional enhancement program that included the "Rapid Eight" effort added the necessary enhancements. These included: a GPS navigation receiver, VHF/UHF radio with VHF/UHF and satellite communications capabilities, and the MIL-STD-1760 databus for weapon on its external pylons [24]. These enhancements allowed the B-52 to carry a variety of weapons including the Have Nap, joint stand-off weapon (JSOW), and joint air to surface stand-off missiles (JASSM) in addition to JDAM guided bombs [24]. Additional enhancements are planned to allow these weapons to be carried internally [28]. With these enhancements, the large internal weapons bay, and the external pylons the B-52 can carry a larger variety of weapons than any other bomber in the US Air Force. A visual comparison of the available bomb bays and the variety of ordinance supported by each of the USAF's strategic bombers is shown in Figure 2.

3.1.3 Modern Electronics Integration

Following the conclusion of the Vietnam conflict the B-52 has received modernization upgrades primarily made possible by the miniaturization of electronics. The development of enhanced computing allows constant communication with resources on the ground and satellites overhead. The B-52 is currently undergoing a computational overhaul to prepare it for operation until 2040. The CONECT program is responsible for integrating the B-52 with "Air Force communication networks and platforms… to receive mission data in flight and retarget weapons" [29]. According to the US Air Force the CONECT program would involve "upgrading the B-52 fleet with tactical datalink and voice communications capability along with improved threat and situational awareness to support participation in network centric operations" [28]. This would allow the B-52 to become and integrated part of the battlefield by allowing information sharing while in-route or over target.

3.2 B-52 Summary

The B-52's mission has changed dramatically from the initial mission to fly higher and faster than enemy air defenses to deliver nuclear weapons in the 1950's to the role it played in Afghanistan which involve loitering over the battlefield to deliver smart weapons for close air support [30].

The B-52 is an example of a system with sufficient excess to successfully evolve to meet new operational requirements for what may be nearly 100 years. It has successfully adapted to: new defensive requirements necessitated by the introduction of SAMs, operation at a more challenging altitude, the introduction of ever more advanced weaponry, and the modern necessity of being electronically connected to an integrated digital battlefield.

This ability to adapt to situations well beyond what could have been envisioned during design points to the excess that was built into the bomber when it rolled off the assembly line. The 2014 Congressional Report summarizes the bomber saying, "The B-52's strengths lie in its diverse capabilities, precision, large payload, and long range; however, if these capabilities remain static, mission effectiveness is likely to erode in the face of 21st century … threats" [31]. Only the ability to continue to adapt has kept, and will continue to keep, the B-52 flying.

4.0 THE F/A-18

The desire for lightweight fighters like the F/A-18 can be traced to just after the Korean War. Planners felt that wars of the future would be fought with new missile technology from beyond visual range. The USAF therefore deemphasized the need for maneuverable air superiority. The Vietnam conflict demonstrated to the Air Force the flaws in their assumptions with repeated losses to inferior North Vietnamese fighters. These losses "galvanized sentiment in the Air Force for a new air-superiority fighter" [32].

As a result, the USAF and Navy pursued the FX programs that led to the development of the F-14 and F-15 fighters that were optimized as air superiority fighters. These fighters were designed to dominate the skies, but were expensive. Their high cost meant that they could only be produced in limited numbers. A group known as the "Fighter Mafia" proposed using cheaper light weight fighters to be mixed in with their more expensive counterparts as part of a "high-low" mix. This alternative ensured sufficient numbers of aircraft would be available for future conflicts with existing defense budgets [33]. The group achieved its goal in 1972 with the release of a Request for Proposals for exactly this kind of fighter.

The final fly-off for the Lightweight Fighter Competition had two competitors: the General Dynamics YF-16 and the Northrop YF-17 Cobra. The result of the fly-off was the selection of the F-16 by the Air Force due to its slightly higher speed and commonality with the F-15 engine [34]. The Navy, however, was unhappy with the decision as they felt it would be too costly to adapt the F-16 for carrier operation. Instead they funded the development of the YF-17 into what would become the F/A-18 Hornet.

The F/A-18 was originally intended to have two variants: one model optimized for the attack role and the other for the fighter role. Sufficient advances in radar design, stores management, and multifunction displays occurred allowing the two models to be merged into a single aircraft [34]. It was equipped with the first all-digital fly-by-wire system and demonstrated high level of reliability and maintainability [35]. The F/A-18 was a versatile system that could fulfill the roles of the F-4 and A-7, both of which it replaced, and was the first modern aircraft with the dual classification of Attack and Fighter.

This context is important for understanding the design preference that designers were using to develop the F/A-18. The aircraft designers were under significant pressure to provide a low cost design that could also to win dogfights, hit ground targets, and operate in the rigorous conditions necessary for carrier operations.

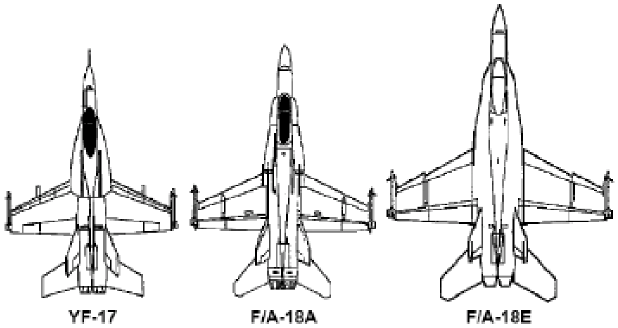


Figure 3. Visual comparison of F/A-18 Mmodels[36]

4.1 F/A-18 Upgrades

After the system was fielded, technology advanced and onboard components needed to be updated with entirely new systems added. Many modifications and enhancements were made to the F/A-18 in the mid 1980's and the new variants were given the new C/D designations. Improvements included: "a revised… ejection seat, improved XN-6 mission computers, upgraded stores management set, an upgraded armament bus (MIL-STD-1553B and -1760), a flight incident recorder and monitoring set (FIRAMS)" [34], a new ECM system (ALQ-165), and a new warning radar [19].

A second round of improvements occurred 1988 which give the Hornet the ability to operate effectively at night giving the modified aircraft the moniker "Night Attack". This package included: GEC-Marconi AXS-9 night vision goggles, two new 5x5 color multi-function display screens, and a color digital moving map display. An infrared pod was added to the right fuselage station which provided a Forward Looking Infrared (FLIR) overlay on the heads-up display. The canopies of the fighters were tinted with gold to help deflect radar energy to minimize radar cross-section. A new software package was also included which combined the sensor information received into an integrated picture of what was occurring outside the Hornet reducing pilot workload and enhancing targeting [19].

Other improvements have been made since the night attack modifications. The APG-65 radar was replaced with the APG-

73 which provided significantly better performance. A "high-resolution synthetic aperture radar" mode was added providing enhanced ground mapping and allowed for "autonomous targeting for the AGM-154 Joint Stand-Off Weapon (JSOW) and the GBU-32 Joint Direct Attack Munition (JDAM)" [34]. A GPS receiver and an enhanced IFF transponder were added along with the capability to carry AIM-120 Advance Medium-Range Air to Air Missile missiles were all incorporated in the mid 1990's [19].

The plethora of modifications supported by the original Hornet demonstrate that the system architecture did provide flexibility for adaptation. It was only when the initial excess for the system was depleted that the system became inflexible.

4.2 Symptoms of Insufficient Excess

The original F/A-18 was officially operational for 5 years before the need for a new design was recognized. The effort was initiated with the "Hornet 2000" study in 1988 and continued into the mid 1990's. The decision to substantially redesign the Hornet faced a great deal of criticism from the GAO which argued that the alternative solution of further modifying the C/D models was cheaper and sufficiently effective to allow time for the development of the next generation warplane.

There were several deficiencies and new external requirements which, individually, could have been rectified or accepted, but in concert they provided sufficient justification to require redesign despite GAO concerns. These shortcomings fell under the categories of: Range/Payload, support for further internal systems growth, and payload recovery. A discussion of these categories and their interplay follows.

4.2.1 Range/Payload

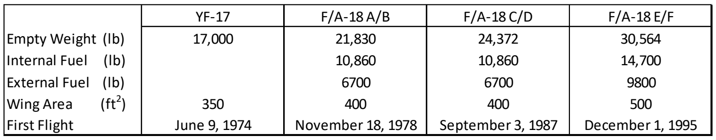
One of the concerns that contributed to the YF-17s loss at the original Light Weight Fighter Competition fly offs was the aircraft's range. The redesigned F/A-18 continued to suffer from a range deficiency during development which was cited in multiple GAO reports [35].

The Hornet faced its greatest range deficit in its attack configuration and the production of aircraft needed to fulfill attack role was nearly canceled. Support from the naval community was sufficient to continue the program, but additional modifications were made to help address the issue during pre-production. These modifications included adjusting the angle of the leading-edge flaps and filling in part of the boundary layer air discharge slots which were found to increased drag. These changes helped to increase range, but also led to a change in air flow such that the vertical stabilizers would eventually experience fatigue issues [19].

Ultimately the Navy accepted the range deficiency in the production model. The rational was that the range was short of what was desired but still acceptable and that aerial refueling would compensate for missions which required longer ranges.

Figure 4 shows that the fuel capacity between the A and C model remained unchanged. The Hornet 2000 study examined the issue of increasing the range of the Hornet. The simplest way to increase range was to add more fuel. This fuel could be added by either increasing the internal storage space allotted for fuel or by increasing the volume of the external tanks carried by the Hornet.

The GAO proposed using larger 480 gallon drop tanks instead of the traditional 330 gallon tanks on the C/D models in order to enhance range without developing a new aircraft. This approach had been taken by the Canadians for the CF-18. The Navy responded that this idea had been studied and that the stress on the aircraft when being catapulted off the deck was "above design limit load" [40]. In order to use the tanks on an aircraft carrier, the airframe of the Hornet would have to be strengthened which would involve added weight and cost.



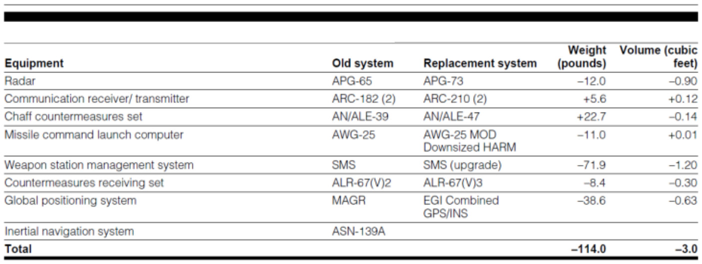
	YF-17	F/A-18 A/B	F/A-18 C/D	F/A-18 E/F
Empty Weight (lb)	17,000	21,830	24,372	30,564
Internal Fuel (lb)		10,860	10,860	14,700
External Fuel (lb)		6700	6700	9800
Wing Area (ft^2)	350	400	400	500
First Flight	June 9, 1974	November 18, 1978	September 3, 1987	December 1, 1995

Figure 4. Comparison of select attributes of F/A-18 models[17,33,35]

4.2.2 Internal System's Growth

As the F/A-18 evolved new systems were added internally to expand the capabilities of the system. This growth led to the prediction in 1992 that by 1996 additional upgrades would have insufficient internal space. Additionally, the Navy claimed that there would be insufficient power and cooling for new systems in the aircraft [19].

The GAO report argued that with modifications and miniaturization of existing systems the C/D models would provide sufficient room. A detailed breakdown of projected growth savings is shown in Figure 5.



Equipment	Old system	Replacement system	Weight (pounds)	Volume (cubic feet)
Radar	APG-65	APG-73	–12.0	–0.90
Communication receiver/ transmitter	ARC-182 (2)	ARC-210 (2)	+5.6	+0.12
Chaff countermeasures set	AN/ALE-39	AN/ALE-47	+22.7	–0.14
Missile command launch computer	AWG-25	AWG-25 MOD Downsized HARM	–11.0	+0.01
Weapon station management system	SMS	SMS (upgrade)	–71.9	–1.20
Countermeasures receiving set	ALR-67(V)2	ALR-67(V)3	–8.4	–0.30
Global positioning system	MAGR	EGI Combined GPS/INS	–38.6	–0.63
Inertial navigation system	ASN-139A			
Total			**–114.0**	**–3.0**

Figure 5. Avionics systems modifications [40]

The GAO pointed to space available in one of the Leading-Edge Extensions (LEX) and extra space that would be available if the fighter were to switch to caseless ammunition for its gun.

The Department of Defense (DoD) countered that space in the LEX and gun bay experienced higher levels of vibration than avionics could with withstand. They also stated their belief that miniaturization of the systems listed above had and would continue to add significant cost to the development of each system. The amount of space added by miniaturizing planned electronic systems would be insufficient to support long term system growth. The DoD was essentially arguing the changes would provide insufficient excess for future adaptations.

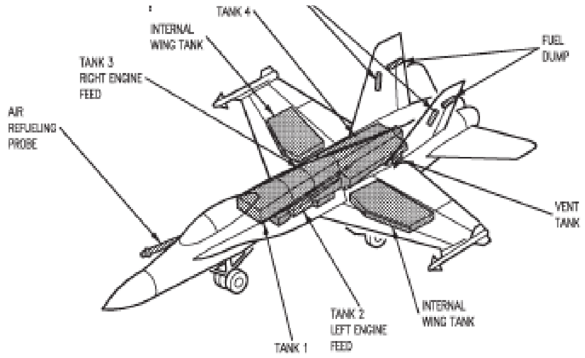


Figure 6. F/A-18 C fuel storage [37]

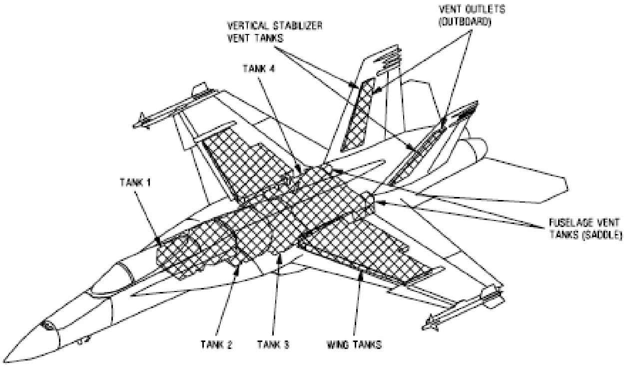


Figure 8 F/A-18 E Fuel Storage [38]

4.2.4 Payload Recovery

Payload recovery is the weight of unused stores, fuel, and external equipment the aircraft can return safely to the carrier. Carrier landings are stressful to the airframe and landing gear due to the sudden acceleration and limits are imposed to minimize the risk of damage.

A Navy official when interviewed about the issue summarized the situation saying that [19]:

> "… the Hornet's bring-back was starting to erode. This occurred, in turn, at the same time we were seeing an increased emphasis on 'smart' weapons as well as increased cost of these weapons. Our options were: 1) land with less fuel, which presented one set of dangers; 2) land with less weapons, which meant dropping unused weapons before landing; or 3) not carrying as much fuel or weapons. None were attractive and all hampered the mission."

The Navy projected that the weight growth of the F/A-18 combined with the weight growth of new weapons had the potential to cause mission planning problems. The original F/A-18C had a payload return capacity of 6,300lbs. Projections from 1992 showed that by 1995 this would be reduced to 5,785lbs by the weight of additional systems.

The weapon systems were also transitioning to precision guided variants. Precision guided weapons are generally constructed by taking a dumb bomb and adding control surfaces and guidance hardware. These modifications add weight to each class of weapon carried. Figure 7 shows the weight difference between the variants that the F/A-18 was qualified to carry.

Guided Bomb	Weight (lb)	Equivalent Dumb Bomb	Weight (lb)	Weight Difference (lb)
GBU-10	2153	Mk-84	2031	122
GBU-12	619	Mk-82	514	105
GBU-16	1131	Mk-83	1005	126

Figure 7. Weight increase of precision munitions [42]

The GAO stated that the Hornet 2000 study suggested the recovery weight for the F/A-18 could be further increased by strengthening the landing gear such that payload recovery could be increased by an extra 3000lbs. The engineering reality was that strengthening the landing gear and airframe would add weight to the aircraft. This weight would further increase the air-speed of the approach and would require a larger wing area to compensate [34] since the Hornet's landing speed started above the original design specification. This spiral would essentially lead to a larger aircraft which is what the Super Hornet already represented.

The Navy did increase the allowable bring-back weight of the original Hornet by 1,000 lbs to allow additional payload recovery through the use of "minor flight control software and procedural changes" [34] but continued growth made this a temporary solution.

4.3 Redesign as F/A-18 E/F

In early 1988 Boeing and the Navy recognized that the current airframe would soon be pushed to its limit. Boeing released a study called "Hornet 2000" in which "… seven configurations were evaluated on a variety of factors, including carrier suitability, strike and fighter missions, maneuverability, systems, survivability, growth, effectiveness, and costs" [19]. From these variants, a new aircraft was designed that combined the best aspects from each design while maintaining affordability.

The designation of E/F was given to this plane even though it was essentially a new design. The F/A-18 E/F had approximately 10% commonality with the F/A-18A. It was 25% larger with a 1/3 fuel capacity boost, larger control surfaces, and a 42% reduction in parts [39].

To address the range shortfall the redesigned Super Hornet included both increased internal fuel capacity and larger external tanks. A 2.3 ft. fuselage plug added some of the extra internal space for fuel [34]. The external tanks were also increased in size from 330 gallons to 480 gallons by using a new filament winding technology with a toughened resin system. The new technology allowed the tank to only increase diameter 3.1 inches and provide the same empty weight. Figures 6 and 8 visually depict the differences in the locations in which fuel is carried in each variant.

The combat radius in the fighter profile increased by 54 nautical miles, and the attack profile range increased by 75 nautical miles with the additional fuel and aerodynamic enhancements [41]. With these modifications, the F/A-18 E/F could meet the design goals for range/payload specified by the Navy.

The F/A-18E/F was also designed from the outset to include space to be filled by the addition or modification of future systems alleviating the absence of space in the original airframe. Boeing reserved 17 cubic feet of internal space along with excess electrical power and cooling capacity [34] to allow the aircraft to evolve successfully without concern for available space or expensive miniaturization.

Finally, the Super Hornet was designed to allow for significantly greater bring back capacity. The maximum carrier landing weight increased to 42,900lbs which despite the heavier airframe allowed almost 200% greater payload return [34].

The changes to the Super Hornet increased the excess available to support future adaptations. It can be argued that the original design should have included more excess and that the changes made in the Super Hornet highlighted in this section are exactly where more excess should have been included. Additional excess would have allowed further adaptation without the need for a costly redesign. The desire to keep the aircraft inexpensive as the low part of the high-low mix, however, pushed the original design away from what may have been a more optimal but also more expensive original design.

4.4 F/A-18 Summary

The initial F/A-18 design was a highly versatile and relatively low cost system succeeding in its objective of the low part of the desired high-low mix. It was capable of operating from an aircraft carrier while performing both fighter and attack roles in a platform that cost $43M per aircraft compared to the E/F model which cost $95M [41]. As a consequence of versatility at low cost, the system had difficulty meeting the initial range/payload goal specified by the Navy.

Evidence suggests that insufficient excess was included in the original design to support evolvability. The symptoms of insufficient excess were: range/payload insufficiency, inadequate internal volume/power for additional subsystems, and eroded payload recovery.

The system was substantially redesigned as the F/A-18E/F variant which added the size necessary to both fulfill initial design objectives and provide excess for future evolutions.

5.0 DISCUSSION AND CONCLUSIONS

The examination of the evolutionary trajectory for the B-52 and F/A-18 reveals two dissimilar paths. The B-52 experienced a lengthy in-service period relative to other strategic bombers while the initial instantiation of the F/A-18 had a relatively short operational period before the need for redesign was recognized. Having covered the history of each system it is now possible to discuss the insights about excess learned from the two paths. The key insights about system design and operation are listed as follows.

1. Ease of change does not ensure system longevity.

The F/A-18A/B was designed with many characteristics to make future evolutions easier to implement. Design decisions like including a digital architecture with a multiplex bus allowed additional sensor and weapons systems to be incorporated with greater ease [43]. Despite these considerations, the original F/A-18 airframe had insufficient design excess in critical areas that did not provide for future system grown and component needs.

Using the F/A-18 as an example a depiction is shown in Figure 9. The base modification cost portion of the graph would be the cost to add/modify a subsystem. This cost is driven by the cost of physical components, qualification, and change propagation. The more change propagates the higher this constant is. All of the modifications for the upgrade to the “C” variant fell within this portion of the graph.

Once weight growth from additional systems reached a certain level compensatory measures were required which incur additional costs. For instance, the Navy would have pilots drop ordinance into the ocean before landing and the allowable bring back was increased causing increased risk to both the system and the pilot. This increasing cost is shown under the compensatory measures portion of the graph.

Finally, the design was pushed to its limit and a substantial redesign was required incurring a step change in cost to add further system resources for future adaptation. System modularity does keep modification cost lower until excess is consumed, but afterward modification costs increase dramatically.

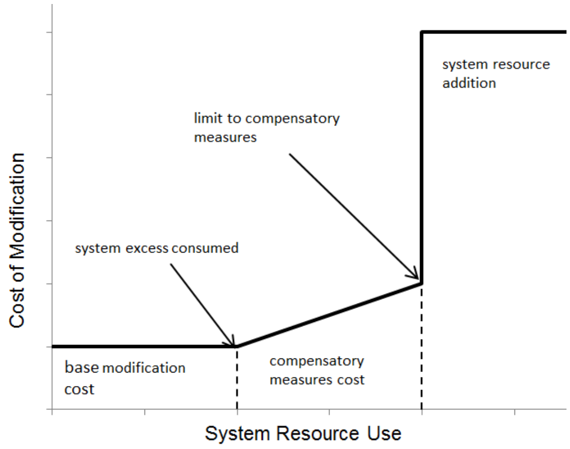


Figure 9. Cost of system modification

2. Change drivers for a system are stochastic in time and severity, but including sufficient excess to support the components necessary for adaptation can increase system longevity.

The performance shortcomings that resulted in the need for the F/A-18 redesign included insufficient internal space, insufficient excess carrier landing speed, and limited range/payload. Each of these performance issues stemmed from a lack of excess incorporated into the original design. It is perhaps true that system growth occurred more quickly with the F/A-18 than with other aircraft, but weight growth is common [44] and provision for it during initial design could have prevented the need for redesign.

In contrast the B-52 included design features that allowed for adaptability. These include a large capacity for weight growth, aerodynamic efficiency allowing for acceptable performance after degradation of additional systems, landing gear placement allowed for carriage of large weapons, structural modifications allowed for durable airframe, high degrees of redundancy, and allowing sufficient internal room for system growth [25]. These features in combination ensured that each challenge to the B-52's system capabilities was at least partially mitigated by the addition of an appropriate adaptation.

3. Specific types of excess have some potential for fungibility.

The performance degradation experienced by the F/A-18 required excess to overcome, but some types of excess could have been used to offset the need for other types. For example, the Hornet was plagued by a shortfall of internal space that was needed both for extra fuel and internal systems growth. As the GAO argued this internal space issue could have been somewhat alleviated with the additional cost for miniaturization of certain components. However, when considered in relation to the other changes that would also be required this, the Navy decided the cost was too great.

If the airframe and landing gear had been designed to be more robust it is possible that larger fuel tanks could have been used to offset the need for more internal space for fuel. A greater wing area could also have allowed for more lift at low speed decreasing the take-off and landing airspeed reducing the forces experienced by the aircraft, thereby allowing larger fuel tanks and again offsetting the need for more internal space for fuel. It is reasonable to hypothesize that identification of these more fungible types of excess may allow the system to support uncertain future changes in a more effective manner than designing excess in all system attributes.

This principle is most pronounced in the B-52 when examining two particular adaptations. The first was the necessary adaptations to survive early SAMs. The change in operational altitude forced designers to reinforce the airframe and skin of the bomber to endure the more challenging environment experience at low altitude. If the B-52 had been designed closer to a weight constraint it may not have been possible for the bomber to add all the necessary weight required for reinforcement. In this way weight excess was traded for structural strength.

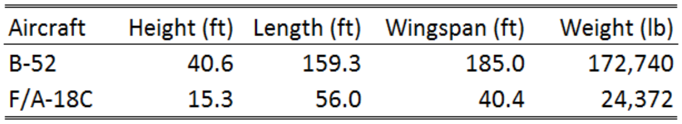
The second was the adaptation to carry additional ordinance by the 'D' variant during the Vietnam conflict. The Big Belly modification created additional internal volume, but additional "volume" was created by carrying ordinance externally on wing pylons. In this way, the structural strength excess was used to offset the need for additional internal volume. Insufficient structural strength to support externally carried ordinance would have reduced the value of the system.

4. The magnitude of potential component resource use should be considered relative to the total quantity inherent in the system.

While the B-52 has experienced significantly more evolution, the two systems were required to overcome similar challenges created by advancing technology. Each experienced system growth to adapt to the need to support precision guided weaponry, night attack capability, and to support the integration with the more data-centric modern battlefield.

These challenges to system performance had similar solutions with similar resource requirements of the two systems. GPS equipment was added to guide precision weaponry, new antennas and electronics were added to support battlefield integration, and additional sensors and displays were added to support night operations. A major difference between the two systems, however; is the magnitude of the component need compared to the system attribute. As seen in a rudimentary comparison in Figure 10 the B-52 is significantly larger and heavier than the F/A-18. Assuming the new components added to each aircraft are roughly the same order of magnitude the relative impact on the total system is significantly higher for the Hornet.

For example, a comparison of an addition to each aircraft of a component with a volume of 200 pounds (roughly equivalent to upgrading a pair of smart bombs) provides an illustrative example. As a fraction of system weight, this represents a 7-fold larger impact on the F/A-18 than the B-52. This finding support the notion that the consumption of excess isn't necessarily a linear function as discussed in previous literature [15].



Aircraft	Height (ft)	Length (ft)	Wingspan (ft)	Weight (lb)
B-52	40.6	159.3	185.0	172,740
F/A-18C	15.3	56.0	40.4	24,372

Figure 10. Comparison of select system attributes [19,45]

To conclude, the examination of the evolutionary trajectories of these systems in the context of their original design has provided insight into what allowed or inhibited the evolvability of each system. These insights underscore the necessity of system excess to allow the system to adapt to change drivers and illuminate the impact that insufficient excess can have on CES design.

System excess should be considered an additional system attribute when planning for a system lifecycle that is complimentary to tools like modularity that reduce the effort required for modifications. Each enables quicker and lower cost modifications of a system but at some additional initial cost.

Since the study of excess is relatively nascent there remain significant areas which require future research. Evolvability is a challenging research area due to the highly stochastic nature of change drivers, the inherent difficulty in modeling complex systems, and challenge of the system specific nature of change drivers and relevant excess types.

This paper contributes knowledge toward reducing the uncertainty for the types and quantities of excess needed for the studied systems, but more research is required to examine a much wider variety of systems to distill generalizations appropriate for generic CES design and then to develop a framework by which to inform design based on those generalized principles.

The goal would be to provide system designers with the knowledge of how to strategically place excess including what types, how much, and where it should be included. This requires a methodology for measuring excess in a theoretical design, providing a means to reduce the uncertainty surrounding the types and quantities of excess likely to be required by future adaptations, and finally a way to quantify the value of excess so that it may be traded against during system design.

ACKNOWLEDGMENT

The authors would like to recognize the National Science Foundation Grant CMMI-1301247 for funding this research. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

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