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THESIS

DETERMINATION OF THE TIMELINE FOR U.S. ARMY AVIATION SYSTEMS TO REACH OPERATIONAL OBSOLESCENCE FOLLOWING TERMINATION OF MODERNIZATION FUNDING

by

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June 2003

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Identifying, countering and preventing operational obsolescence is a challenging but vital task for personnel involved in the design, acquisition and support of military equipment. In this thesis, I define the concept of operational obsolescence and show quantitative relationships between modernization funding timelines and operational obsolescence.

Only if we truly understand obsolescence can we best combat its onset and effects. I use example data from both legacy and current Army Aviation Systems to draw conclusions about the impacts of particular modernization timelines on the various forms of obsolescence that cause operational obsolescence. I then make recommendations concerning the optimal modernization strategies for current and future aviation systems in order to facilitate the Army's ability to field and sustain the most tactically and logistically superior weapon systems possible.

Using first principles, I construct Life Models based on hazard functions for each of the different forms of obsolescence. I then combine these models into an overall model, and discuss the design of a data system to estimate model parameters.

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DETERMINATION OF THE TIMELINE FOR U.S. ARMY AVIATION SYSTEMS TO REACH OPERATIONAL OBSOLESCENCE FOLLOWING TERMINATION OF MODERNIZATION FUNDING

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ABSTRACT

Identifying, countering, and preventing operational obsolescence is a challenging but vital task for personnel involved in the design, acquisition, and support of military equipment. In this thesis, I define the concept of operational obsolescence and show quantitative relationships between modernization funding timelines and operational obsolescence.

Only if we truly understand obsolescence can the U.S. Army best combat its onset and effects. I use example data from both legacy and current Army Aviation Systems to draw conclusions about the impacts of particular modernization timelines on the various forms of obsolescence that cause operational obsolescence. I then make recommendations concerning the optimal modernization strategies for current and future aviation systems in order to facilitate the Army's ability to field and sustain the most tactically and logistically superior weapon systems possible.

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EXECUTIVE SUMMARY

Identifying, countering, and preventing operational obsolescence is a challenging but vital task for personnel involved in the design, acquisition, and support of military equipment. In this thesis, I define the concept of operational obsolescence and describe quantitative relationships between modernization funding timelines and operational obsolescence.

Operational obsolescence may be defined in simplest terms as the loss by a working system of its ability to perform its mission successfully and affordably. My research indicates that there are eight major sub-types of obsolescence that affect weapon systems. These sub-types and their individual definitions are:

1. **Tactical** inability of a given system to adequately perform the tactical mission assigned to it; includes the characteristics of the system not meeting required doctrinal parameters.

2. **Logistical** inability of a weapon system to be maintained and supported within time-, spare part, and manpower-feasibility constraints.

3. **Economic** inability to maintain acceptable readiness levels due to increased costs as availability falls, making parts too expensive to retain in required quantities.

4. **Functional** designed function is no longer necessary or adequate; includes the system being interoperable with other related systems.

5. **Technological** revolutionary changes in what we know how to make, how we employ systems, or what we have available in design and support cause fundamental obsolescence.

6. **Political** use and support of weapon system becomes too hard to justify or the designed purpose becomes unacceptable on the world stage.

7. **Mission Change** weapon system meets other definitions but due to there being no follow-on alternative, we are forced to absorb high modernization costs and continue to use otherwise obsolete systems.

8. Service Specific varying missions and philosophies between Services cause a system to be obsolete for one Service while not so for another.

Using first principles, I construct Life Models based on hazard functions for each of the different sub-types of obsolescence. Each contributing sub-type is modeled as a two-parameter continuous distribution. The distributions used are the Weibull, Lognormal, and Logistic. I show plausible shapes for the hazard function of each sub-type plotted against time, based on speculated parameters from historical examples of weapon systems that have fallen victim to a particular sub-type of obsolescence.

The sub-type models are then combined into an overall model, using the idea of competing failure rates. The hazard functions for each of the sub-types sum to give the overall hazard function for the weapon system. This methodology requires that the components are statistically independent. I make the necessary simplifying assumption that the sub-types are independent to display analytical techniques for my models.

In order to make use of my thesis a data system must be constructed and published to estimate model parameters for various types of weapon systems and to continue the research begun in the production of this thesis. U.S. Army Materiel Systems Analysis Activity (AMSAA) should develop a database of obsolescence data from approximately forty years of weapon system life cycle data, either historical data from legacy systems or data on current systems. I recommend the use of historical data so that this process can be used in the near future.

Once data are available and parameters are estimated for the models developed, these models will estimate the distribution and time to obsolescence for any weapon system under study, as well as the dominant and contributing sources for that obsolescence.

I conclude from the information currently available, and based on my expert opinion, that we should make our initial attacks on the issue of logistical obsolescence, particularly as we field increasing technologically advanced systems that rely heavily on electronic components.

I recommend striving to develop a methodology that allows continuous refreshment of components over the life cycles of weapon systems through spares replacement, which can be continuously upgraded and modernized by our contractors. This gives both the Army and industry the most competitive and capable environment in which to work and perform our mutually supportive and mutually dependent missions.

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I. INTRODUCTION

A. BACKGROUND

Acquisition, Logistical Support, and Operational personnel charged with development and sustainment of war-fighting capabilities within the U.S. Army strive to avoid operational obsolescence of the systems for which they are responsible. A large degree of effort is currently spent on assessing the impact of logistical obsolescence, particularly as it applies to small electronic components of complex systems. Tactical and functional viability of current and emerging weapon systems receives significant attention from Project Managers (PM) and the testing community. But there is much more to operational obsolescence than logistics and tactics. To the best of my knowledge, operational obsolescence has never been fully defined, much less studied. The deeper we delve into the question of what constitutes operational obsolescence, the more complex it becomes. Clearly, operational obsolescence could be defined to simply mean the loss by a working system of its ability to perform its mission successfully, and at acceptable cost. But as we look closer at this issue, it becomes apparent that the reasons for this loss are many and varied. Therefore, we must start by adequately defining the major factors influencing operational obsolescence. We then examine how to identify the impending occurrence of each sub-type of obsolescence, and how to avoid or counter it.

B. SCOPE

What is the appropriate definition of the term "Operational Obsolescence" as it applies to U.S. Army Aviation systems? For example, is an aircraft more likely to first become obsolete because it genuinely can no longer perform the tactical task for which it was designed, or a related task? Or will it reach a point when it is obsolete because it is no longer either possible or economically feasible to maintain acceptable readiness levels due to logistical reasons? Do technological advances, either friendly or enemy, make other systems so much more desirable that the original system should be divested? Is it true that an aircraft is obsolete as soon as one of these types of obsolescence occurs? Are these answers different for Attack aircraft versus Cargo or Utility aircraft? In the next chapter, I list and define the most pertinent of the various types of obsolescence that weigh on this problem, using well-known systems, both air and ground, as particular examples.

There are many issues that must be addressed in an attempt to identify and combat operational obsolescence. This thesis answers a number of them. I have also included a comprehensive listing of what I consider the most important of the remaining issues in my recommendations for further study in Chapter V of this thesis. I strongly recommend continued study into this critical area by subsequent researchers.

The objectives of my thesis were to:

1. Define operational obsolescence and its sub-types.
2. Develop plausible models of the individual types of operational obsolescence, and combine these models into an overall model.
3. Analyze the combined model to determine quantitative relationships between modernization and operational obsolescence.
4. Draw conclusions from my analysis and make recommendations to avoid the onset and effects of operational obsolescence.

C. PURPOSE

According to the Project Manager's Office for the Longbow Apache, the sponsoring agency for this thesis, operational obsolescence as an all-encompassing phenomenon has never been studied, analyzed or quantified. I found no existing information on operational obsolescence during the literature-search phase of my research. We currently have no quantifiable assessment of the impact of operational obsolescence on the war-fighting strategies and capabilities of our military forces. This phenomenon has become increasingly important to both Congressional and Military Decision-makers who must gain maximum effect over weapon systems' life cycles in the most economically-feasible manner.[1] This thesis provides, for the first time, an analytical assessment of what operational obsolescence is, what its impacts are, and what the Army can do to best avoid or minimize these impacts. Without this analytical effort,

[1] LTC Patrick J. Garman, Project Manager, Longbow Apache, Program Executive Office, Aviation, Redstone Arsenal, AL, Personal Interviews, NOV-DEC 2002.

the Army will continue to use a best-guess, reactive approach to the design, acquisition, and support of current and near-term future weapon systems.

The urgency for accurate information concerning the phenomenon of operational obsolescence is great. This thesis provides initial insight into this troubling area. Due to the lack of actual weapon system data to use in my models, it is not possible for me to solve the problem of operational obsolescence for any particular system. The value of this thesis lies in showing how the problem of operational obsolescence can be solved, once data are available.

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II. DEFINITIONS AND DISCUSSION

A significant portion of the value of my thesis lies in the introduction and definition of the concept of operational obsolescence. The selection and definition of the various sub-types of obsolescence that drive overall operational obsolescence are largely drawn from my experience and judgment and that of my primary thesis advisor, along with relevant information gained from available literature. Sources other than my advisor and me will be specifically noted and credited, as applicable.

A. TACTICAL OBSOLESCENCE

1. Definition

The first type of operational obsolescence is "Tactical Obsolescence." We define this term as the inability of a given system to adequately perform the tactical mission assigned to it and its crews. This includes the characteristics of the system no longer meeting required doctrinal parameters for firepower, mobility, crew protection, etc. as applied to current tactics, techniques, and procedures (TTP) of the user. These requirements often evolve as doctrine changes. A good example of a system that succumbed to tactical obsolescence is the M113A2 Armored Personnel Carrier.

2. Example

The M113A2[2] is a 13-ton, tracked vehicle designed to transport Infantry soldiers rapidly over the battlefield while affording them protection from direct and indirect small arms and artillery fires. When introduced in 1960, this concept was a huge tactical advancement for previously foot-bound Light Infantry soldiers who possessed high mobility but were restricted to a movement rate of only a few kilometers per hour and who were highly vulnerable to even the lightest of fires. Infantrymen were now able to move as an entire small unit at tens of kilometers per hour and the vehicle would repel or absorb the impacts of some, but not all, previously lethal fire.

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[2] Jane's Information Group, Limited, "Jane's Armour and Artillery," 22nd Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2001-2002, pp. 380-383.

This vehicle served the U.S. Army well for many years, but today the U.S. Army considers it obsolete for the tactical purpose of serving as an Infantry Fighting Vehicle. The vehicle was first modernized from the M113 to the M113A1 in 1964, less than five years after initial fielding, due to power and safety concerns. Fifteen years later the vehicle was modernized to the M113A2 configuration. Within a total of twenty-three years the M113A2 was tactically obsolete because of the emerging tactical needs of the U.S. Army for Infantry Fighting Vehicles, due to firepower and mobility shortcomings. Although the vehicle can conceptually still be maintained to acceptable standards, it is obsolete because it cannot meet the operational requirements of current Infantry doctrine. Specifically, the vehicle does not possess a high-firepower weapon system that can be employed while under the armor protection of the carrier; soldiers onboard the M113A2 cannot effectively employ their individual weapon-systems from inside the carrier; enemy munitions have advanced to the point where there are too many threat weapon which readily penetrate the vehicle's armor; and the vehicle is loud, fuel inefficient, and its surfaces are easily detected. Thus, the M113A2 can no longer perform its assigned, or a closely related mission, to acceptable tactical levels for the U.S. Army, although in modernized versions it continues to serve as a combat service support vehicle and continues to find roles within the armies of other nations.

There are many other examples of major systems that have become tactically obsolete. I use the M113A2 only as a representative of this class of obsolescence. Due to the lack of accumulated data, there is no definitive mean time when weapon systems reach tactical obsolescence, but the value appears to be on the order of approximately fifteen to twenty years. Note in this definition that tactical obsolescence may be reached due to advances in friendly doctrine, such as the requirement for mounted weapon systems and weapon fire, or due to enemy advances, such as improvements in munitions or detection capabilities.

B. LOGISTICAL OBSOLESCENCE

1. Definition

A war-fighting system loses operational relevance whenever it cannot be maintained and supported in time-, spares, and manpower-feasible manners. The inability to meet mission parameters within these constraints we term as "Logistical Obsolescence." As any mechanical system ages, its components wear and break. These components must either be repaired or replaced. Most war-fighting systems have no civilian equivalent and are often designed for a specific military mission or purpose. Once the required number of systems is produced, production lines are shut down, often including the production of repair parts, or spares. A number of problems may result. The required repair parts may become so hard to obtain that it is virtually impossible to maintain acceptable system-availability levels to make the system operationally relevant in war or crisis. The components required to produce a particular repair part may no longer be available, at any price, due to the components themselves no longer being manufactured, or being superceded by more technologically advanced parts. This issue is particularly pervasive in the arena of electronic components and computer processors, which comprise the majority of the subsystems on modern Army aircraft.

2. Example

The AH-64D Longbow Apache Attack Helicopter, first fielded in July 1998 to the 1-227th Aviation Regiment(Attack), is comprised almost entirely of computerized assemblies and electronic components, assembled into collections of boxes of integrated circuit cards performing mutually supportive tasks.[3] This is a significant difference from the largely mechanical systems of previous Army aircraft. These boxes are collectively known as Line-Replaceable-Units (LRU) or Shop-Replaceable-Units (SRU), depending on whether the particular component is authorized for stockage and replacement at the level of the using operational unit or at higher echelon maintenance elements. Although the Longbow Apache is a relatively young weapon system, due to its high dependence on electronic components and the rapid pace of technological advancement in the computer market, several of its LRU/SRUs cannot be sustained due to non-availability of the electronic parts required to repair or construct the boxes.[4] These boxes must either be redesigned, at tremendous time and cost penalties, or known obsolete parts must be purchased in sufficient quantities to maintain repair stocks. Either way, the aircraft, in its

3 Jane's Information Group, Limited, "Jane's All the World's Aircraft," 91st Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2000-2001, pp. 462-464.

4 LTC Patrick J. Garman, Project Manager, Longbow Apache, Program Executive Office, Aviation, Redstone Arsenal, AL, Personal Interviews, NOV-DEC 2002.

current configuration, has reached the point of logistical obsolescence, at an age of less than five years.

Analysis of available information shows that if we define a weapon system to be logistically obsolete when either we can no longer obtain applicable repair parts through existing supply channels due to them being superceded or the parts on the weapon system are one or more full generations behind available electronics capabilities, the point of logistical obsolescence can occur even before Initial Operational Capability (IOC) or shortly thereafter.[5] According to Gordon Moore's Law that has been used as a rule of thumb for the current lifespan of any generation of electronic parts, electronic parts get twice as fast and half as costly approximately every eighteen months.[6] This rule has been observed to hold quite well for the last four decades, and it is believed that it will hold for at least the next two decades. Thus, weapon systems that rely heavily on electronic components can expect to approach logistical obsolescence of one form or the other within six to eighteen months of final design and to be extensively affected within two generations of their components, or three years, of fielding, unless there is significant modernization of components.

C. ECONOMIC OBSOLESCENCE

1. Definition

Another, closely related, type of operational obsolescence is "Economic Obsolescence." Following initial fielding of a weapon system in a particular configuration, the required repair parts may increase in cost as availability falls, even if they are still logistically relevant from a design and capabilities perspective, making them too expensive to retain in required quantities. As a typical military weapon system ages, its failure rate increases. This implies that the amount of time that the system is available to perform its mission relative to the number and duration of times that it requires unscheduled maintenance goes down. As the Mean Time Between Failures (MTBF) parameter for any weapon system drops significantly, the system becomes less

5 Tommy W. Filler, Multi-year II Program Manager, U.S. Army Apache Production Programs, The Boeing Company, Mesa, AZ, Personal Interview, 6-8 DEC 2002.

6 Gordon E. Moore, Cramming More Components Onto Integrated Circuits, Published in "Electronics," April 19, 1965. pp. 2-4.

economically feasible to support and use, especially if a more supportable and capable system can be designed and fielded.

2. Example

A good example of economic obsolescence is found in examination of the UH-1H "Huey" Utility Helicopter.[7] This venerable system served the U.S. Army remarkably well for nearly forty years in a variety of roles ranging from troop-transport to cargo hauling, medical evacuation, and even gunship roles. It still serves other U.S. Services and a number of allies in lower operational tempos and lower risk missions than those for which the U.S. Army used the aircraft. However, as the aircraft aged and its components broke, spares became much more difficult to obtain and the aircraft spent more and more time in the hangar versus its time on the flight line or in the air. As a result, although the aircraft could theoretically still perform its assigned mission in an acceptable manner from a tactical perspective, it was not logistically and economically sound to continue to support it. It was ultimately divested from the Army in favor of the newer, more capable, and far more economically supportable UH-60 "Blackhawk." The U.S. Army's search for a more economically sound utility helicopter began approximately fifteen years into the life cycle of the UH-1. The UH-1H aircraft was deemed to be economically obsolete beyond recovery after some thirty-five years of service.[8] Note that although logistical and economic obsolescence both relate to the ability of the supply system to provide spares to support the weapon system, there is a distinction. In the case of logistical obsolescence, we are defining the point of obsolescence to be when the required spares are either no longer available, at any price, or when they are no longer competitive with current design standards. Economic obsolescence occurs when spares can be obtained and are relevant, but either the availability has diminished to the point where the parts are unacceptably expensive or too frequent demands for the spares by an individual weapon system makes it too costly to continue to support the weapon system. Once data are available, more detailed study should be performed to determine the precise relationship and point of separation of these two sub-types of obsolescence.

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7 Jane's Information Group, Limited, "Jane's All the World's Aircraft," 91st Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2000-2001, p. 360.

8 Ibid.

D. FUNCTIONAL OBSOLESCENCE

1. Definition

Another type of operational obsolescence is "Functional Obsolescence." This occurs when advancing technology or associated doctrine make a designed system function no longer necessary or adequate. This includes the ability of a system to interoperate with other related or co-located systems.

2. Example

A good example of this type of obsolescence is the AN/PRC-77 Portable FM radio system, a mainstay of Army Light and Mechanized Forces for many years.[9] As other radio systems emerged and evolved, the PRC-77, designed for single frequency, unsecured, line-of-sight communications, no longer had a function on the modern battlefield. More modern radio systems operated with organic voice-scrambling security devices, further enhanced by their ability to rapidly frequency-hop over a common set of frequencies that all members of an organization used, and used non-line-of-sight technology for long-range communications. Thus, the PRC-77 no longer had a valid function within the doctrine of its users after some twenty-five years of service. The PRC-77 was able to sustain relevance up to a point through add-on devices such as the KY-57 Voice Security Device. However, once the standard for voice communication required frequency-hopping systems, the PRC-77 was obsolete. The PRC-77 maintained functional relevance for a long time because it operated during a period of relative stability in terms of communications functions. This condition does not presently exist and future functional requirements are likely to evolve much quicker than the twenty-five year life of the PRC-77. Also note the distinction between tactical and functional obsolescence. In the example of the M113A2, the functional requirement for an Infantry Fighting Vehicle remains relevant, but the M113 could not tactically meet the functional requirement. In the case of the PRC-77, the U.S. Army no longer had any functional requirement for a single frequency FM radio, and the PRC-77 was not interoperable with the Single Channel Ground and Airborne Radio System (SINCGARS) frequency-hopping secure FM communications systems.

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9 Jane's Information Group, Limited, "Jane's Military Communications", 23rd Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2002-2003, p. 72.

This type of obsolescence can even befall a system early in its designed life. For instance, considerations for the Army's Objective Force, centered on network-centric forces utilizing the Future Combat System (FCS) may make the "Stryker" vehicle's functionality incompatible with evolving battlefield functionalities in less than five years, even though it is a new system. Of potentially even greater significance, FCS requirements have the potential to relegate main battle tanks (MBT) to functional obsolescence. The Army's ground warfare tactics have been designed around heavily armored tanks since World War II, but the weight, footprint, and logistical requirements of heavily armored vehicles may make their functional concept for strategic deployment obsolete as the Army fields lighter, more readily deployable and supportable systems, all tied together with network-centric tactics that rely more heavily on superior information than on superior armor.[10] The recent Iraq War "Iraqi Freedom" again showed the high value of heavily armored vehicles when our forces are engaging military forces armed with more than small arms; and this point deserves careful consideration by senior military and government leadership. We are not prepared in 2003 to trade 50-tons of armor protection for any quantity of information, but this may change as the Department of Defense and the U.S. Army progress towards Objective Force Transformation.

E. TECHNOLOGICAL OBSOLESCENCE

1. Definition

Technological Obsolescence is yet another form of operational obsolescence. This form of obsolescence has to do with revolutionary changes in what we know how to make, how we can employ war-fighting systems, or what we have available in the design and support of systems.

2. Example

For instance, the development of the turbine engine near the end of the Second World War made whole classes of highly capable fighter and bomber aircraft near-instantaneously obsolete. Such systems as the P-51 "Mustang", P-38 "Lightning" and B-29 "Super-Fortress" that enjoyed fearsome reputations during WWII for their agility,

[10] United States Army White Paper, *Concepts for the Objective Force*, General Eric K. Shinseki, Chief of Staff, U.S. Army, November 2001, pp 9-10.

firepower and speed became old, slow relics in a matter of a few years. Much faster and more reliable aircraft that could carry larger weapons payloads further and more economically were fielded in a short period of time. The introduction of nuclear weapons made whole strategies and groups of strategic weapons obsolete overnight. High payload, precision guided missiles made the Navy's 16-inch guns, along with the Battleships that carried them, operationally obsolete simply because technology offered a better and more reliable answer to the same questions that the 16-inch gun was fielded to answer.[11]

F. POLITICAL OBSOLESCENCE

1. Definition

A particularly complex, but nevertheless highly important, form of operational obsolescence is "Political Obsolescence." This occurs whenever either the use and support of the weapon system becomes unacceptably hard to justify to American Taxpayers or the designed purpose of the weapon becomes politically unacceptable on the world stage, even though the weapon is capable of its purpose and is supportable.

2. Example

Two excellent examples of this form of operational obsolescence, for different reasons, are the Army's AH-1 "Cobra" Attack Helicopter and the Air Force "Pershing II" Intermediate Range Nuclear Missile. The Cobra could deliver devastating firepower against enemy armored formations and was conceptually supportable from a logistical perspective, if modernized, but the burden of the Army justifying to Congress and the American people the support and use of both the Cobra and the AH-64 "Apache" Attack Helicopters became unjustifiably high. Therefore, the politically astute position for the Army was to voluntarily divest itself of the older and less capable Cobra and "put all of its eggs into the Apache's basket." The Cobra lost its role as the Army's premier attack helicopter after nineteen years of service, and was completely divested from all Army combat aviation forces thirty-two years after it was initially fielded.[12] In the case of the

11 David L. Schrady, Distinguished Professor, Operations Logistics, Naval Postgraduate School, Personal Interview, 1 October 2002.

12 Jane's Information Group, Limited, "Jane's All the World's Aircraft," 91st Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2000-2001, pp. 361-363.

Pershing II, although the capabilities of an intermediate range nuclear missile were highly desirable to America's forces, the world political situation made the planned usage and continued placement of these missiles on American bases around the world unacceptably expensive in terms of political clout. They were, therefore, removed and destroyed for diplomatic, rather than military operational, reasons; only ten years after initial fielding.[13]

G. MISSION-CHANGE OBSOLESCENCE

1. Definition

A very important consideration in the definition and declaration of operational obsolescence is changes in the mission of weapon systems over time, as well as the existence of an "heir-apparent" follow-on system. No system can be removed from active service due to operational obsolescence, unless, as in the case of the Pershing, its entire mission goes away, until there is a better system to fill the void created by the removal of the current system. Also note at this point, I am not equating the terms "obsolete" and "useless." A weapon system may still be capable of performing a necessary function and may have to be supported as presently equipped. Thus, it is not useless, but is nevertheless obsolete, in that there exists a more effective and efficient alternative. We often see excellent examples of this in the forces of our enemies. The 2S6 Air Defense System has made the ZSU-23-4 obsolete, and certainly the T-55 Tank is obsolete in forces which possess T-72 Tanks. These obsolete systems still serve useful and dangerous roles for some of our enemies, but this does not diminish the fact that they are obsolete by reasonable definition.

2. Example

There are many examples of aging systems that continue to receive modernization funding and logistical support well after they meet the basic criteria of some of the definitions given. The B-52 "Strato-Fortress" Bomber and C-130 "Hercules" Transport have each served the U.S. Air Force for almost fifty years. Both have received many expensive upgrades and vast amounts of logistical support. They require "patchwork" fixes to their wing spars and landing gear, and many major new subsystems have been

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[13] Jane's Information Group, Limited, "Jane's Strategic Weapon Systems", 34th Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2001, p. 588.

designed and incorporated into the aircraft. Nevertheless, despite being far older than the men and women who crew them, these aircraft are still a mainstay of the U.S. Air Force war-fighting fleet.[14] This remains so because no acceptable designs have been proposed which can perform the same required functions as economically as continuing to support these old airplanes. Therefore, they soldier and serve on. Over their exceptionally long life cycles the B-52 and C-130 have continually been modified and modernized to allow them to maintain relevance in the face of evolving tactics and strategies.[15] Note here that the B-52, unlike the other examples where systems have been declared obsolete, is used as an example of a system that likely should have been declared obsolete under sub-type definitions, but has not been because there is no other system that can fully replace it. This fact has cost the U.S. Air Force great sums of modernization dollars, and as a result it is even more difficult to justify the decision to divest the aircraft from the force even after the point where divestment is otherwise prudent.

H. SERVICE-SPECIFIC REQUIREMENTS OBSOLESCENCE

1. Definition

In this same arena, varying missions from one Service to another in the U.S. Department of Defense may cause an aircraft to be obsolete for one Service while not so for another.

2. Example

For reasons previously addressed the Army has completely divested itself of AH-1 aircraft, while the U.S. Marine Corps is still upgrading, designing and fielding ever more modern versions of this same weapon system. This is so simply due to the different missions and philosophies of the two respective Services. The United States Marine Corps primarily uses attack helicopters for close in fire support coordination in serial and ground escort operations, particularly in amphibious ship-to-shore movements and subsequent shore operations within the objective area. The Marine Corps must pay close attention to the footprint and volume of its aircraft due to the necessity to park and store

14 Alan R Washburn, Professor, Operations Research, Naval Postgraduate School, Personal Interview, 30 September 2002.

15 Jane's Information Group, Limited, "Jane's All the World's Aircraft," 91st Edition, 1340 Braddock Place, Suite 300, Alexandria, VA 22314-1651, USA, 2000-2001, p. 388.

them on Light Helicopter Amphibious (LHA/LHD) ships. The United States Army, on the other hand, considers its attack helicopter battalions as major maneuver forces, using them in heavy anti-armor roles, conducting both close-in and deep attacks, primarily at night, and fighting integrated with mechanized forces in reconnaissance and attack missions. Although the Army has concerns for the size and footprint of its combat aircraft, the fact that the Army's aircraft are parked and maintained primarily on land at airfields or in relatively spacious tactical assembly areas poses fewer size constraints than those faced by the Marine Corps.

Table 2-1 summarizes the sub-type definitions of operational obsolescence.

Type of Obsolescence (O_i)	Definition	Example
i = :		
1. Tactical	inability of a given system to adequately perform the tactical mission assigned to it; includes the characteristics of the system not meeting required doctrinal parameters.	M113A2
2. Logistical	inability to be maintained and supported within time-, spares, and manpower-feasibility constraints.	AH-64D
3. Economic	inability to maintain acceptable readiness levels due to increased costs as availability falls, making parts too expensive to retain in required quantities.	UH-1H
4. Functional	designed function is no longer necessary or adequate; includes the system being interoperable with other related systems.	PRC-77
5. Technological	revolutionary changes in what we know how to make, how we employ systems, or what we have available in design and support cause fundamental obsolescence.	P-51D
6. Political	use and support of weapon system becomes too hard to justify or the designed purpose becomes unacceptable on the world stage.	Pershing
7. Mission Change	weapon system meets other definitions but due to there being no follow-on alternative, we are forced to absorb high modernization costs and continue to use otherwise obsolete systems.	B-52
8. Service Specific	varying missions and philosophies between Services cause a system to be obsolete for one Service while not so for another.	AH-1

Table 2-1. Table of Definitions and Examples of Types of Obsolescence

This table summarizes the definitions and examples discussed in detail in the text of Chapter II of this thesis.

III. DEVELOPMENT OF MODELS AND DATA STRUCTURE

A. BACKGROUND

1. Models

There are no existing models used to describe or analyze operational obsolescence or any of its sub-types. I have, therefore, produced models for each of the sub-types of obsolescence, using first principles to construct these models. Each sub-model is a probability distribution from the two-parameter Weibull, Lognormal, or Logistic Distributions. The desired shape of the hazard function of each of the models is shown, along with sufficient descriptive detail to show why each model is believed to be plausible for its particular sub-type of obsolescence. The grand model for operational obsolescence is the product of all of the sub-models taken in sequence. This allows for easy and detailed analysis, and will permit future researchers or users to tailor the model to their particular systems and purposes. It is a very simple process to substitute other continuous distributions into the model, if desired.

To produce my models I used hazard functions that describe the likelihood of each sub-type of operational obsolescence occurring in the next small unit of time, given that we know that obsolescence has not occurred up to the present time, to model obsolescence due to the various different causes. It is possible to characterize the probability distribution for failure time, *T*, by cumulative distribution functions, probability distribution functions, survival functions, or hazard functions. All of these types of functions are important for various purposes. For this thesis, I have developed my models from hazard functions, which are then used to obtain the survival, or reliability, function.

2. Functions

a. Cumulative Distribution Function[16]

The cumulative distribution function (cdf) of *T*, represented by $F(t) = \Pr(T \leq t)$, gives the probability that a system will become obsolete before time *t*.

[16] Wallace R. Blitschke and D.N. Prabhakar Murthy, "Reliability Modeling, Prediction and Optimization," Wiley Series in Probability and Statistics, 2000, p. 28.

b. Probability Density Function[17]

The probability density function (pdf) for a continuous random variable *T* is defined as the derivative of *F(t)* with respect to *t*, i.e., *f(t) = dF(t)/dt*. The pdf can be used to represent relative frequency of failure, or in our case, obsolescence, times as a function of time. The pdf is perhaps less important than the other functions for applications in reliability of systems, but is used extensively in the development of technical results. The cdf at *t* is computed as the area under the pdf curve from 0 to *t*, thus giving the probability of failing before time *t*. Thus:

(3.1) $$F(t) = \int_0^t f(x)dx$$

c. Hazard Function[18]

The hazard function, *h(t)*, also known as the hazard rate, instantaneous failure rate function, or other similar names, is defined as follows:

(3.2) $$h(t) = \lim_{\Delta t \to 0} \frac{\Pr\left(t < T \le t + \Delta t \mid T > t\right)}{\Delta t} = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)}$$

where Δt represents any small change in elapsed time, *f(t)* is the probability density function of the phenomenon under analysis, *F(t)* is the cumulative distribution function, and $R(t) = 1 - F(t)$.

The hazard function gives us the propensity of the weapon system to become obsolete in the next small increment of time, given that it has not become obsolete up to time *t*. Thus, for small Δt,

(3.3) $$h(t) \cdot \Delta t \approx \Pr(t < T \le t + \Delta t \mid T > t).$$

The hazard function for the Weibull distribution is:[19]

(3.4) $$h(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta - 1}, t > 0.$$

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17 William Q. Meeker and Luis A. Escobar, "Statistical Methods for Reliability Data," Wiley Series in Probability and Statistics, 1998, p. 28.

18 Ibid, pp. 28-29.

19 Ibid, p. 86.

$\beta > 0$ is a shape parameter, and $\eta > 0$ is a scale parameter. When $0 < \beta < 1$, the Weibull has a decreasing hazard function. When $\beta > 1$, the Weibull has an increasing hazard function. The larger the value of the shape parameter, the more sharply the hazard function grows exponentially, as can be clearly seen in the hazard function formula in equation 3.4. At precisely $\beta = 1$, the Weibull describes the exponential distribution.

The lognormal cdf and pdf are:[20]

(3.5) $$F(t;\mu,\sigma) = \Phi_{nor}\left[\frac{\log(t)-\mu}{\sigma}\right],$$

and

(3.6) $$f(t;\mu,\sigma) = \frac{1}{\sigma t}\phi_{nor}\left[\frac{\log(t)-\mu}{\sigma}\right], t > 0,$$

where ϕ_{nor} and Φ_{nor} are the pdf and cdf, respectively, for the standardized normal. The median, $t_{.5} = \exp(\mu)$ is a scale parameter and $\sigma > 0$ is a shape parameter. The lognormal hazard function starts at 0, increases to some point in time, and then decreases, eventually to 0. For σ large, the hazard function reaches a maximum early and then decreases. Detailed information on the distributions used in the production of my models may be found in Appendix A.

d. Cumulative Hazard Function[21]

The hazard function gives a point estimate of the obsolescence probability at a specific point in time. For our purposes it is useful to calculate the cumulative hazard function, represented by *H(t)*, which will allow us to derive the total accumulated probability of obsolescence up to a particular time *t*. That is,

(3.7) $$H(t) = \int_0^t h(x)dx$$

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20 Ibid, pp. 82-83.

21 Ibid, p. 29.

e. Reliability Function[22]

The survival function, or reliability function, which I represent as *R(t)*, gives the probability of a particular system still being operationally relevant beyond a given time *t*. This is precisely the information we need to study both obsolescence due to particular sub-types of obsolescence and overall operational obsolescence. If we have the hazard function we can easily obtain this reliability function, as follows:

(3.8) $$R(t) = \exp\left[-H(t)\right] = \exp\left[-\int_0^t h(x)dx\right] = 1 - F(t).$$

B. DATA STRUCTURE[23]

In order to make full use of the information in this thesis, the reader must understand the definitions given for each of the sub-types of obsolescence that drive the umbrella concept of operational obsolescence. Then each individual user or organization must set the criteria for the obsolescence forms they are interested in analyzing, and collect data from either applicable historical systems or current systems to apply to the models developed. Obsolescence processes are modeled on a continuous scale, but data will always be discrete. Thus, the user may find it convenient to partition the total time line over which they are concerned with obsolescence into intervals. The length of the intervals will depend on evaluation time cycles, measurement precision, and the like, but, in general, will appear as: $\{(t_0, t_1], (t_1, t_2], \ldots (t_{m-1}, t_m], (t_m, t_{m+1})\}$, where $t_0 = 0$, or the start of the period, and $t_{m+1} = \infty$.

For example, if obsolescence times are measured to the nearest month, then each interval would be one month long, up to t_m, the last recorded time. The last interval is, of course, of infinite length and covers all times after the final recording. The intervals do not all have to be the same length. Let us define:[24]

(3.9) $$\pi_i = \Pr(t_{i-1} < T \le t_i) = F(t_i) - F(t_{i-1})$$

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22 Ibid, p. 28.

23 Ibid, pp. 32-33.

24 Ibid, p.33.

as the multinomial probability that any weapon system will become obsolete in interval *i*. Note that all $\pi_i \geq 0$ and $\sum_{j=1}^{m+1} \pi_j = 1$. The reliability function evaluated at t_i is

(3.10) $$R(t_i) = \Pr(T > t_i) = 1 - F(t_i) = \sum_{j=i+1}^{m+1} \pi_{j.}$$

Then,

(3.11) $$p_i = \Pr(t_{i-1} < T \leq t_i \mid T > t_{i-1}) = \frac{F(t_i) - F(t_{i-1})}{1 - F(t_{i-1})} = \frac{\pi_i}{R(t_{i-1})}$$

is the conditional probability that a weapon system will become obsolete in interval i, given that the system was not obsolete at the beginning of interval i. Note that this means that p_{m+1} = 1, but the only restriction on $p_1 ... p_m$ is that $0 \leq p_i \leq 1$. Thus, it is easy to see that:

(3.12) $$R(t_i) = \prod_{j=1}^{i} [1 - p_j], i = 1, ..., m + 1.$$

The π or p values above may be used as alternative sets of basic parameters to model discrete obsolescence point data. The parameters used in my models are those from the distributions indicated, and their description may be found in any basic statistical reference book. In general, all of my models use two parameters, the first representing the shape of the distribution, and the second, representing the scale of the distribution.

C. OBSOLESCENCE MODELS

Because the understanding and analysis of operational obsolescence is new, there is little to no data to analyze in my models. I use expert opinion, based on my judgment and study of the example weapon systems, to develop representative parameters to illustrate the analytical techniques that follow. I am specifically not proposing that these are the correct parameters for each of the sub-types of obsolescence. I am merely demonstrating what I believe to be plausible shapes and relative scales for each of the forms of obsolescence that drive operational obsolescence.

1. Tactical Obsolescence

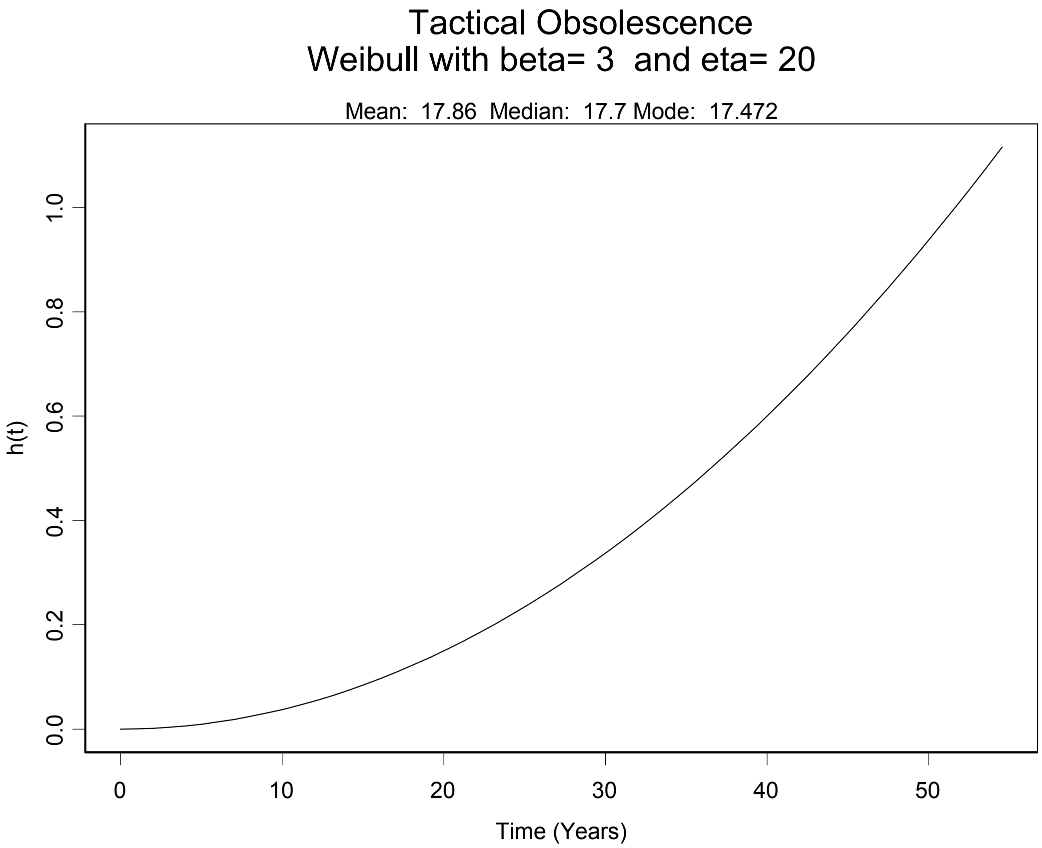

Figure 3-1. Graph of the Hazard Function for Tactical Obsolescence

Figure 3-1 shows Tactical Obsolescence modeled as a Weibull Distribution with shape parameter = 3, and scale parameter = 20. These parameters were chosen to obtain the shape and estimated mean time to obsolescence presented in the text that follows; using the example weapon system information. Measures of centrality are printed at the top of the box. Note that for this distribution the shape parameter also gives the point in time when we expect there to be a 63.2% chance of obsolescence due to this sub-type.

With regard to Tactical Obsolescence, when a new weapon system is fielded our enemies will begin virtually immediately to learn all they can about the new system and its capabilities. Once they are comfortable with their understanding of our new weapon system, they will begin developing either a counter-weapon system or a modification to their tactics to attempt to overcome our new weapon system. Success is never assured, but there is a positive probability that they will succeed in the endeavor. I believe that this probability will logically increase at an increasing rate with time.

Given that we will always attempt to develop both optimized hardware and optimized tactics during our concept development and Operational Testing and Evaluation (OT&E) phases of the fielding process for new weapon systems, based on current and emerging threats and our current logic for capabilities-based forces, I will assume that the weapon system is the best we can make it at the time of fielding. Thus, operational obsolescence risk starts at or near zero, and increases at an increasing rate as time advances, without any plateaus, and under the assumption that no modernization occurs. The shape parameter value of 3 is simply a model for obsolescence under conditions where we expect an increasing risk of obsolescence at an increasing rate as time passes. This value causes the ratio of time to the scale parameter to be squared in the Weibull hazard function formula shown in equation 3.4. Thus, with a scale parameter of 3, we see a quadratic increase in the risk of the weapon system becoming obsolete in the next small increment of time.

2. Logistical Obsolescence

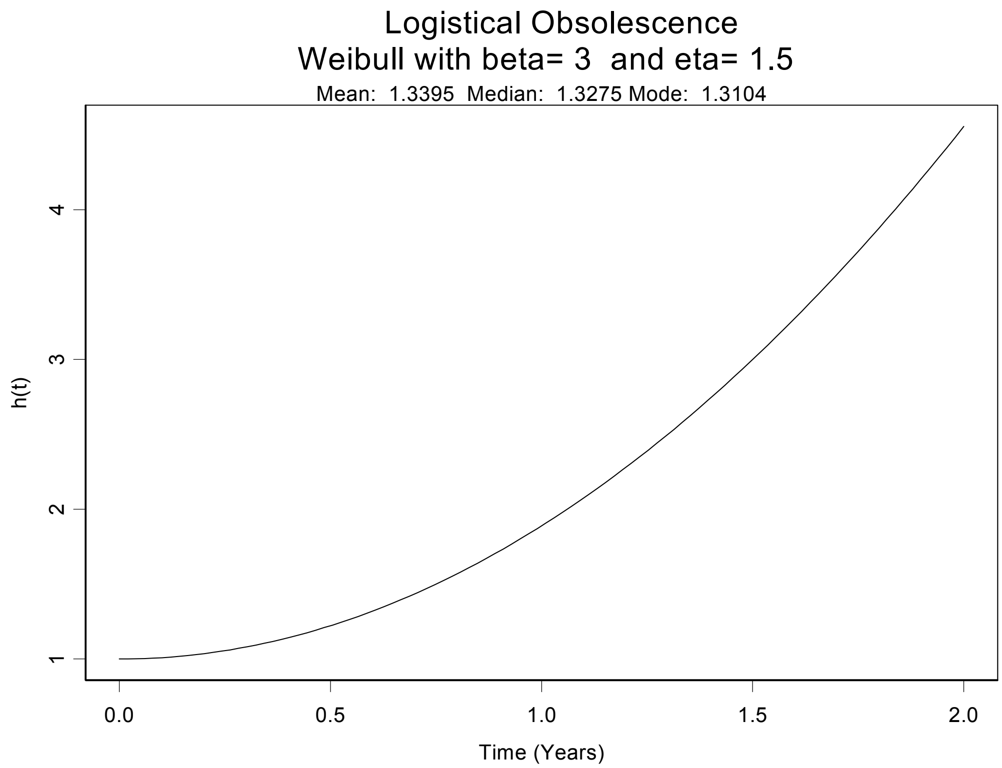

Figure 3-2. Graph of the Hazard Function for Logistical Obsolescence

Figure 3-2 shows the model for logistical obsolescence. The estimated shape parameter is the same as for tactical obsolescence, but the scale is much smaller. A scale parameter of 1.5 means that there is a 63.2% chance the system will be obsolete after 18 months. This reflects the effects reported by Project Manager Office personnel and major contractors and is consistent with Moore's Law. Note the drastic change in the horizontal axis of this graph as compared to Figure 3-1, although the shape of the curve is identical. This displays the relative roles of the shape and scale parameters.

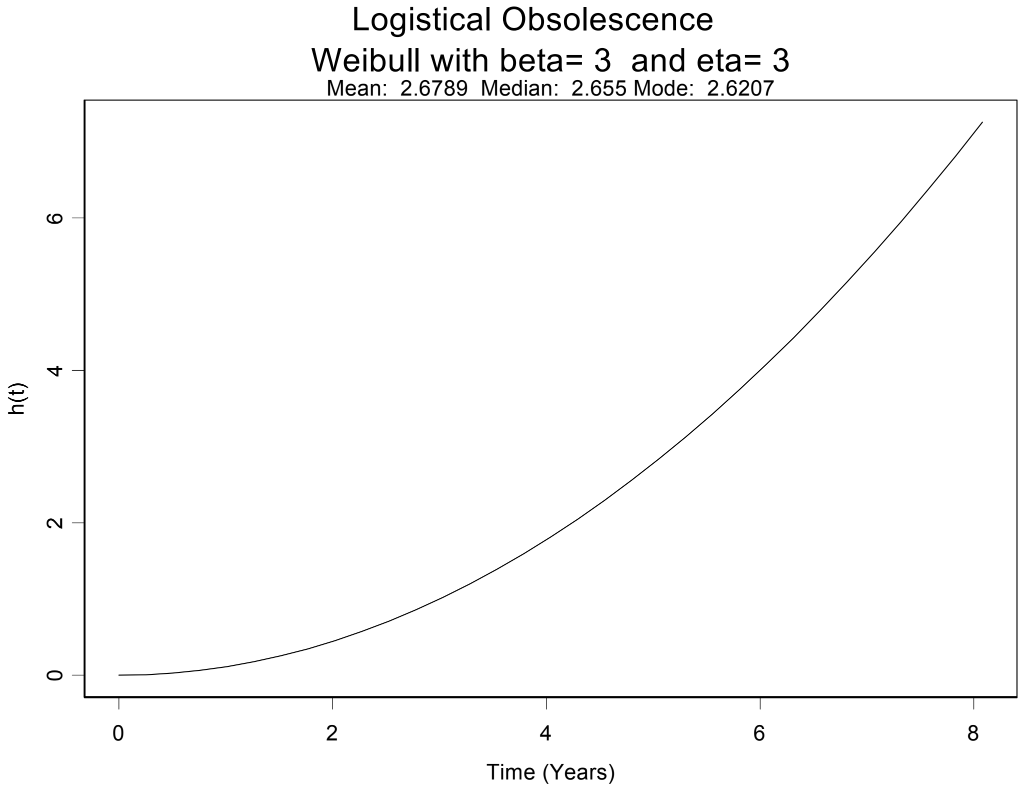

Figure 3-3. A Second Graph of the Hazard Function for Logistical Obsolescence

Figure 3-3 shows the hazard function for logistical obsolescence with the improved system for purchasing and maintaining spares for electronic components. The scale parameter has been doubled, resulting in the measures of centrality being twice as large as those from Figure 3-2.

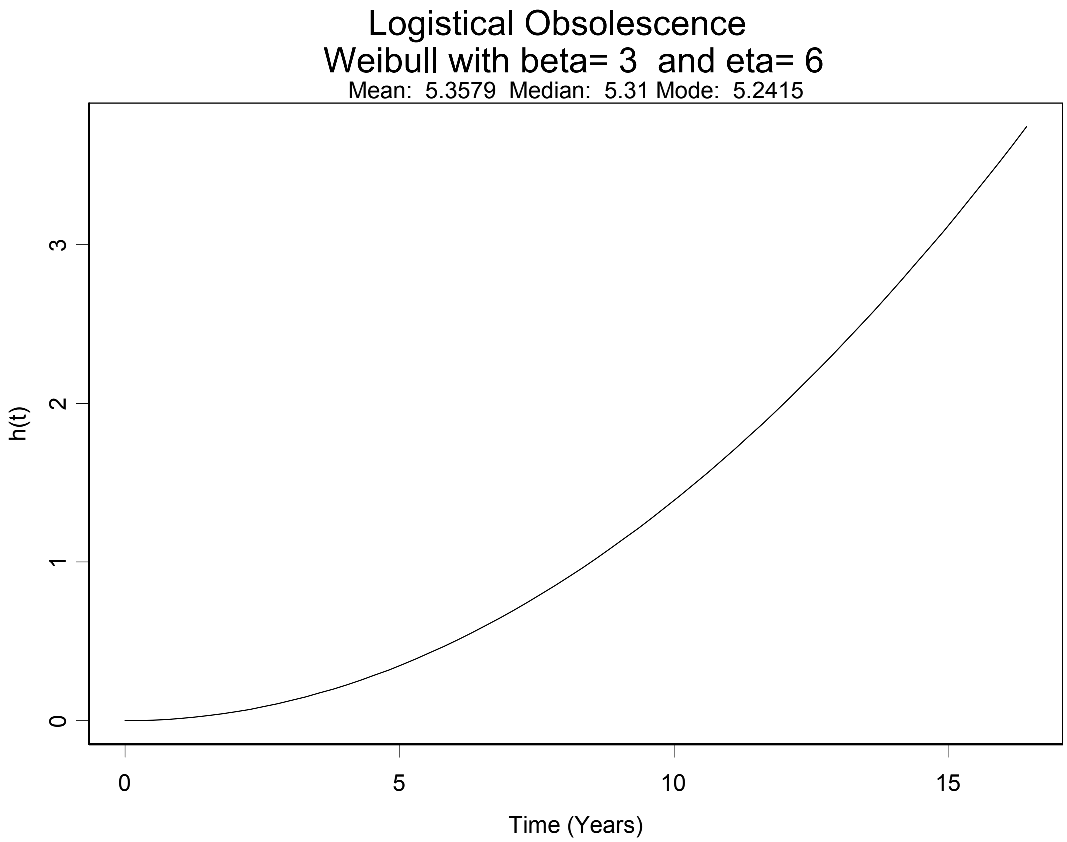

Figure 3-4. A Third Graph of the Hazard Function for Logistical Obsolescence

Figure 3-4 shows a third model for logistical obsolescence in which two simultaneous improvements in the logistical system results in a quadrupling of the original scale parameter. Such an improved logistical design gives us a four-fold increase in the estimated time until modernization is required due to logistical obsolescence of the system.

Due to the large numbers of component parts in all sub-systems of any weapon system, particularly one that relies heavily on electronic components, there is a very real risk of a weapon system suffering from logistical obsolescence from the moment is it fielded, and perhaps even prior to fielding. Parts required to build components and systems may be superceded or may no longer be produced in their original form by sub-contractors.[25] Therefore, the risk of logistical obsolescence increases rapidly at an increasing rate with the passage of time. This sub-type will dominate the model unless the weapon system is frequently modernized, or production plans have a specific counter-

25 Tommy W. Filler, Multi-year II Program Manager, U.S. Army Apache Production Programs, The Boeing Company, Mesa, AZ, Personal Interview, 6-8 DEC 2002.

obsolescence section, which may include large buys of all critical parts. In Figure 3-2, I have shown the estimated graph of the hazard function for logistical obsolescence versus time under conditions where we have carefully and deliberately purchased all electronic components anticipated to both manufacture and sustain all production vehicles in a multi-year (MY) contract. This one action should at least double the scale parameter of the hazard function, i.e., double the expected time to operational obsolescence due to logistical obsolescence simply because acceptable current generation components will now be available in sufficient quantities to produce and support the systems fielded under the MY contract. In Figure 3-3, I have shown the estimated effect of taking this same step along with the added step of purchasing cutting edge electronic components immediately before beginning the MY production. Such a "just-in-time modernization update" is estimated to at least quadruple the initial scale parameter of the logistical obsolescence model, resulting in a two generation, or approximately four-fold, extension of the relevant life of the weapon system before significant modernization would be required. Under this methodology we would capture one electronic component generation for each of the two actions of having the most current proven generation of electronic components immediately before commencing production and purchasing the components in sufficient quantity up front to produce and support all production vehicles in the contract. Note that the multiplicative increase in the scale parameter will be a function of the number of years specified in the MY contract. The above example anticipates a MY buy of only one full component generation. A MY contract extended over five years would see the scale parameter increased 3.33-fold. The down-side is that the longer the MY contract the more difficult it would be to anticipate needs and developments during the life of the contract, and the larger an amount of "accepted obsolescence" would occur during the period that we were holding component advancement static.

Of particular value is the concept of designing weapon systems so that electronic components could be modernized through spare part replacement with enhanced components well into the future by requiring contractors to maintain form, fit, and function of all parts, along with extensive use of open-architecture design that allows integration of new parts from any number of contractors or sources. This single step, the difficulty and complexity of which should not be taken lightly, could ensure that our weapon systems maintained logistical relevance throughout their life cycles, and could save large sums of modernization dollars in contrast to designing and using system specific and military specification components. If successful, attainment of this process would essentially remove logistical obsolescence from the weapon systems' reliability model; causing any ensuing obsolescence to be properly placed under technological obsolescence. Obsolescence due to spares would now occur due to such a significant technological advancement that the new part represented a revolutionary jump in how we design and support weapon systems.

3. Economic Obsolescence

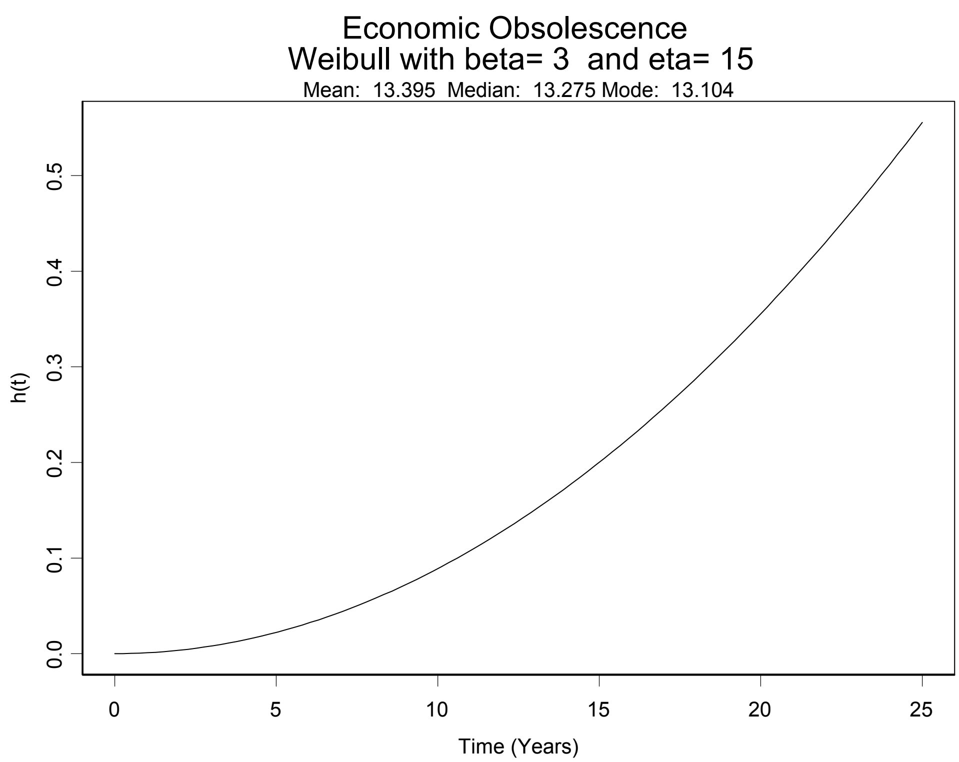

Figure 3-5. Graph of the Hazard Function for Economic Obsolescence

Figure 3-5 shows the individual model for economic obsolescence. The shape is the same as for logistical obsolescence but the much larger scale parameter represents the belief that the system will not be vulnerable to economic obsolescence until much later in its life cycle.

The risk of Economic Obsolescence is near zero immediately following initial fielding because fielding plans will include an Operations and Sustainment (O & S) Plan and Budget which should prevent the immediate onset of obsolescence. There is a strong relationship between economic and logistical obsolescence because if the same parts required to avoid logistical obsolescence are not purchased in sufficient quantity upfront, they will become non-economically feasible to requisition and stock. Therefore, logistical and economic obsolescence have the same shape, but the scale is different. Even under these conditions, I believe that the onset of economic obsolescence lags several years behind the onset of logistical obsolescence. I assess these two sub-types of obsolescence to be independently but not identically distributed, as described in Chapter II. I recommend further research to draw the remaining distinctions between these two sub-types for use in my models after data are available. The risk of economic obsolescence is felt to increase over time at an increasing rate, perhaps particularly so after a certain point, which may be found to be the critical O&S point for a given weapon system. This possibility should also be examined and determined in a later effort.

4. Functional Obsolescence

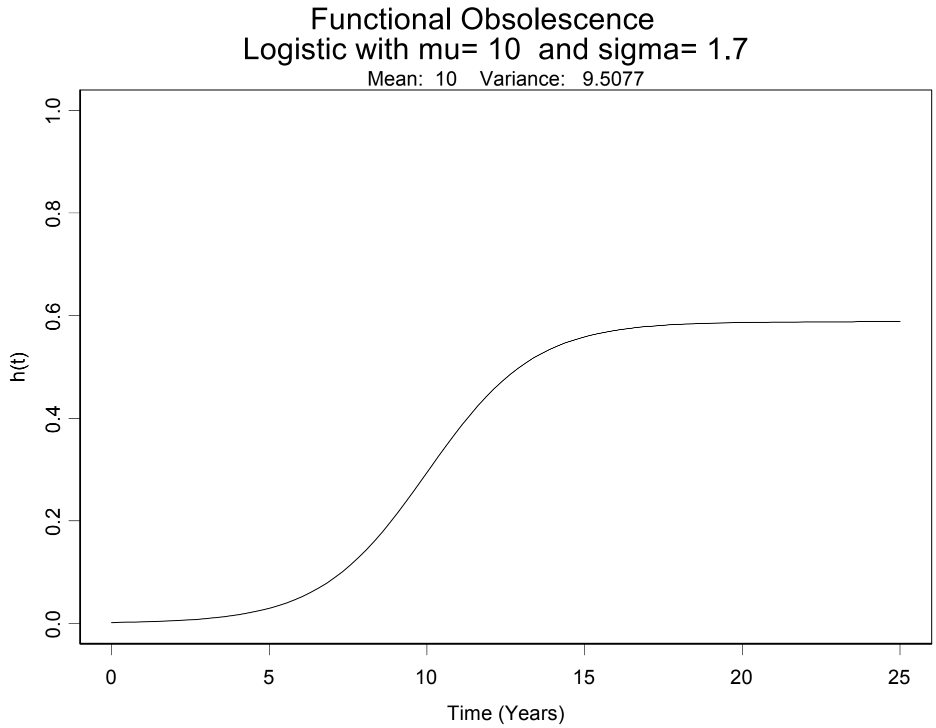

Figure 3-6. Graph of the Hazard Function for Functional Obsolescence

Figure 3-6 shows the model for functional obsolescence, which reflects that the risk of functional obsolescence is initially low; increases rapidly during the middle portion of a weapon systems life cycle; and then given that it has not occurred after more than ten years converges to an asymptotic value dependent on the particular weapon system.

Functional obsolescence initially enjoys some of the same advantages as tactical obsolescence as a result of the search for optimization during design and OT&E. We may assume that weapon systems are always fielded to meet a valid functional requirement and that this function is deemed relevant well into the foreseeable future. However, functional requirements can unexpectedly change as defense strategies, technology, etc. evolve. Therefore, the risk of functional obsolescence for a given weapon system will always start at zero and the risk may be considered to have a small, but positive probability in the early portion of the weapon's life-cycle. This risk will increase to a significant level as time advances. After a weapon system has enjoyed successful deployment for a number of years, believed to likely be somewhere in the neighborhood of ten to fifteen years, the risk of functional obsolescence continues to increase, but at a decreasing rate, as tactics and supporting weapon systems are developed around the functionalities and capabilities of successful major systems. Functional obsolescence is a continuous risk throughout the weapon's life cycle, but unlike most of the other sub-types is never guaranteed to occur as certain functional requirements may exist for decades allowing weapon systems designed to meet these requirements to maintain functional relevance throughout even a protracted life cycle.

5. Technological Obsolescence

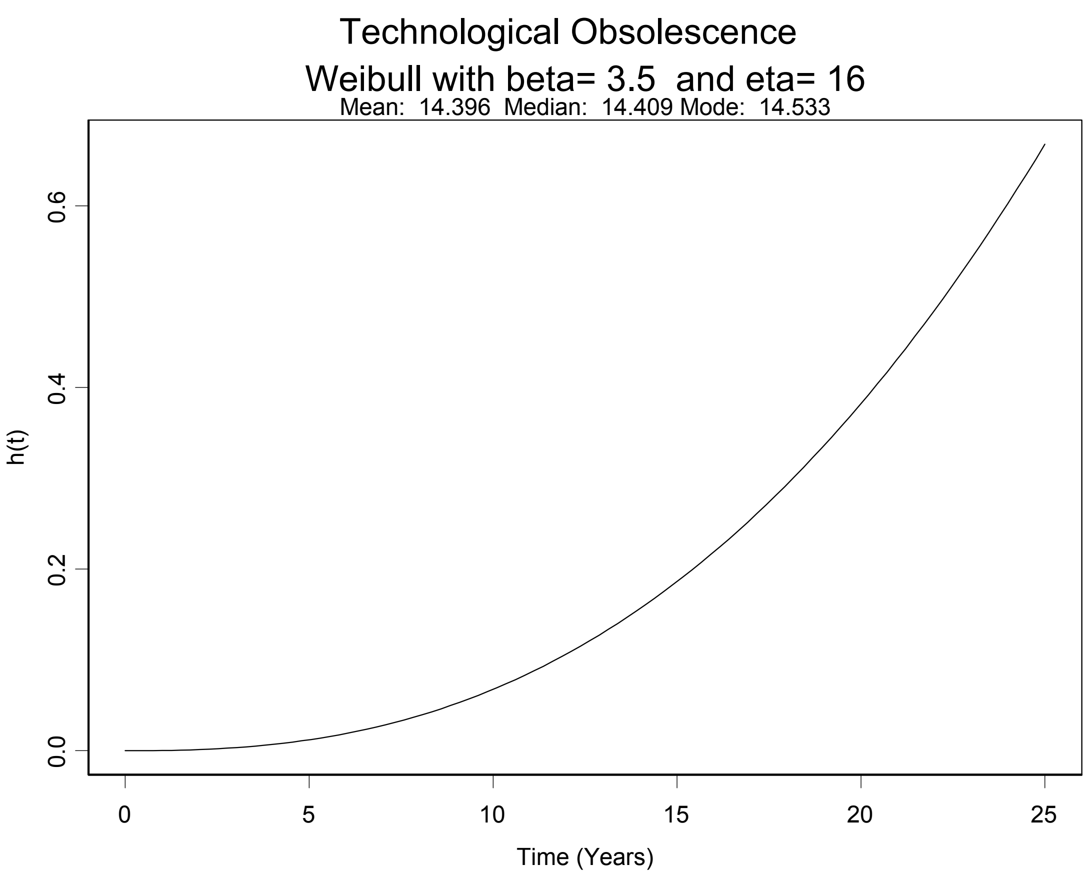

Figure 3-7. Graph of the Hazard Function for Technological Obsolescence

Figure 3-7 shows the model developed for technological obsolescence. This model reflects the belief that the risk of obsolescence likely increases slightly more

rapidly than that of the previous sub-types of obsolescence due to the rapid pace of technological discovery and advancement, but over roughly the same scale.

We must clearly differentiate between true technological obsolescence and logistical obsolescence driven by advancing technology. These are not the same thing! Technological obsolescence occurs not when an existing technology gets better, but when a revolutionary technological breakthrough occurs or becomes mature enough to be militarily useful and reliable. Such an event calls for existing weapon systems within the mission area of the breakthrough to be completely redesigned or face a high likelihood of being easily and thoroughly defeated on the battlefield. There appears not to be any available data or even hypotheses among aviation contractors as to the mean time between major technological breakthroughs or the probability of a revolutionary technological event occurring in any given time frame.[26]

Technological obsolescence receives some protection through the meticulous search for the most imaginative capabilities feasible during the weapon system's concept development. Therefore, the initial risk is very low. The risk of technological obsolescence increases at a slow but increasing rate with time. Technological obsolescence is eventually virtually assured if the weapon system is not modernized.

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26 Tommy W. Filler, Multi-year II Program Manager, U.S. Army Apache Production Programs, The Boeing Company, Mesa, AZ, Personal Interview, 6-8 DEC 2002.

6. Political Obsolescence

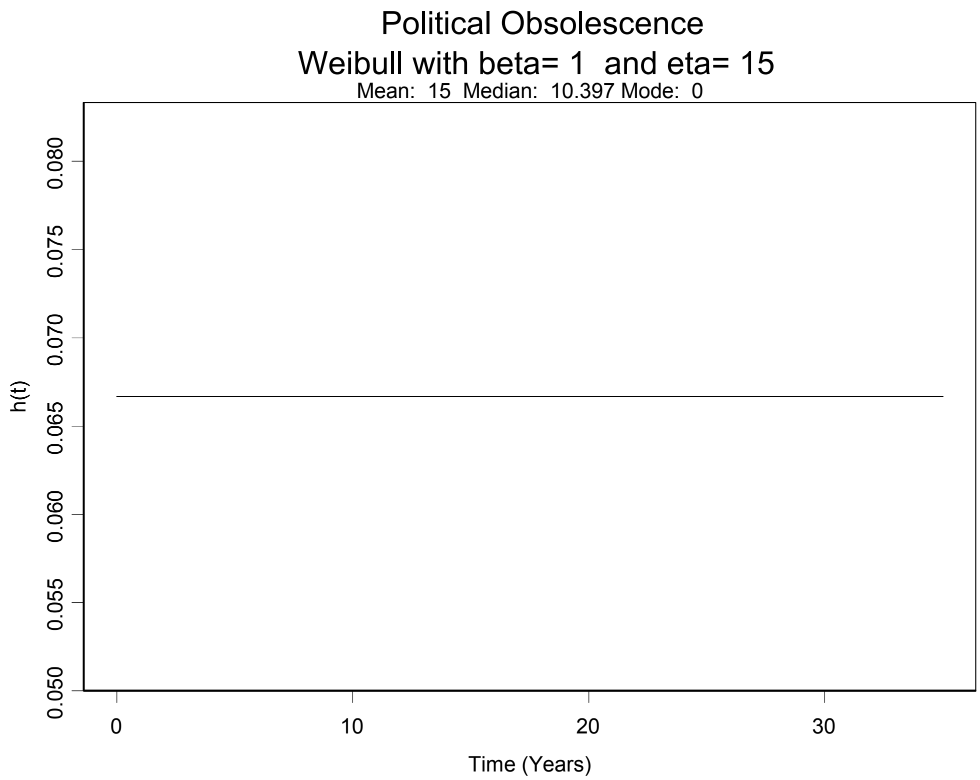

Figure 3-8. Graph of the Hazard Function for Political Obsolescence

Figure 3-8 shows the model for political obsolescence. The shape parameter of "1" shows that the obsolescence hazard is exponential. Therefore, political obsolescence may occur with little warning at any point in the weapon system's life cycle. Historical review of example systems was used to estimate the mean of this sub-type of obsolescence. This is a particularly difficult form to design and plan against.

Political Obsolescence is particularly dangerous and devastating. It is often much more difficult with political obsolescence than with other sub-types to detect and avoid the impending occurrence of a catastrophic obsolescence event. However, once a weapon system is declared to be politically obsolete it must generally either be destroyed or modernized in such a dramatic sense that it barely resembles its original form. Political obsolescence may follow a conflict in which the weapon was used, probably to great success but at tremendous cost to one side or the other. It may also simply occur during peacetime when the global political climate becomes altered by some event. The risk of political obsolescence is unpredictable, but is a constant and significant risk throughout the life cycle of any weapon system. This is why the shape parameter will always be one, representing the exponential distribution, which represents potential occurrences at anytime throughout the weapon system's life cycle. The best plan to avoid political obsolescence may well be seeking to develop non-overlapping weapon systems, which are particularly effective in a given role, but produce very low avoidable collateral damage and little or no lingering effects following their use in a conflict. The rate of political obsolescence varies widely by type and design of weapon system. For instance, weapons of mass destruction and area fire weapons are likely much more vulnerable to political obsolescence than are rifles and trucks. Landmines are increasingly threatened with this type of obsolescence, although they may be relatively invulnerable to other sub-types.

7. Mission Change and Lack of Heir Apparent Systems

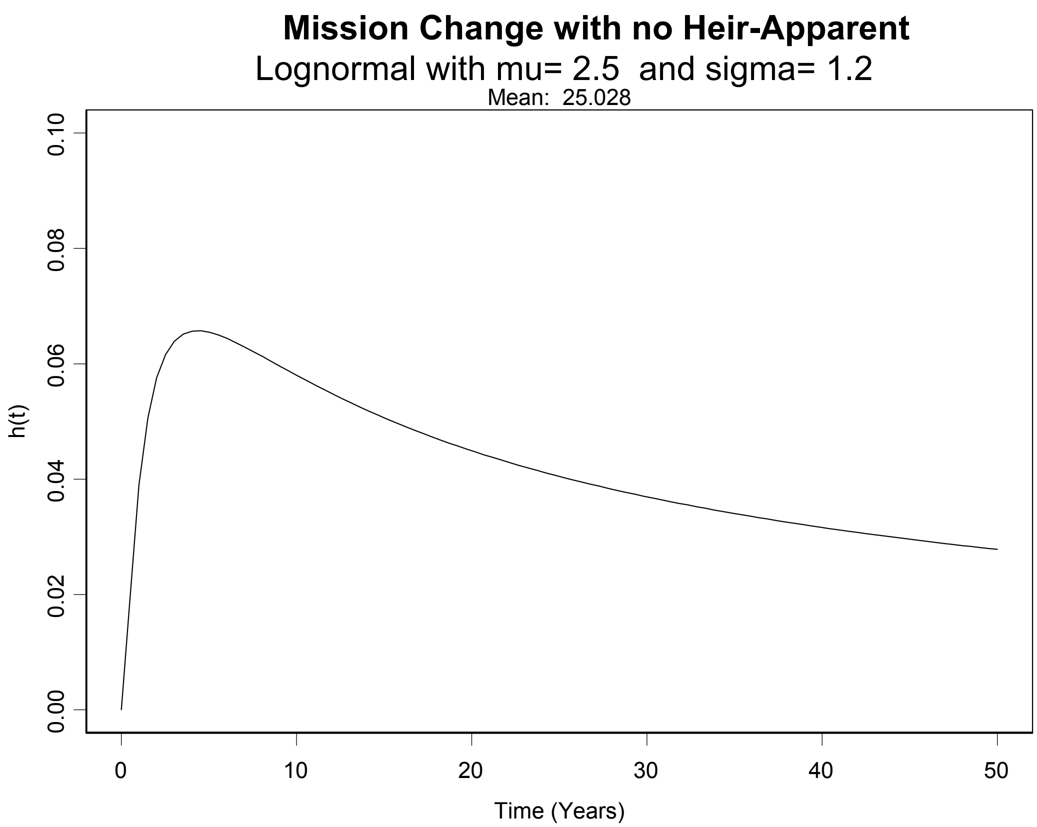

Figure 3-9. Graph of the Hazard Function for Obsolescence due to Mission Changes with no Heir-Apparent

Figure 3-9 shows the model for obsolescence due to significant changes in the weapon system's mission, particularly in the absence of a follow-on replacement weapon system. The risk of obsolescence due to changing missions will increase rapidly in the early portion of the weapon systems life cycle and then decrease rapidly given that the system has not been divested, eventually asymptotically approaching zero after many years of successful usage since if the system is heavily modernized multiple times to perform changing missions and no heir-apparent emerges, it becomes increasingly difficult to justify divestment of the system.

Weapon systems may be assigned to roles and functions quite different from those that the weapon system was initially fielded to perform. Successful accomplishment of these tasks and roles may not be possible in the absence of significant modernization. For the purposes of this thesis, I will assess the risk of operational obsolescence due to mission change following termination of modernization funding for the weapon system under consideration. I see this as a near zero risk initially but having a rapid and increasing risk during the early years of the weapon system's life cycle. The risk will increase up to a maximum level, followed by constant or decreasing risk. As previously noted, there are numerous examples of aircraft systems that undergo substantial mission changes without an economical and effective heir-apparent replacement system which can perform the modified mission as well as the existing system. If a weapon system has no heir-apparent and its mission changes substantially following termination of modernization funding, we will be faced with having to accept a certain degree of risk of obsolescence while we continue to use the weapon system. Generally, the decision to make substantial changes to a weapon system's mission profile must be accompanied by the decision to renew modernization efforts in order to accomplish the new mission.

8. Service-Specific Influence

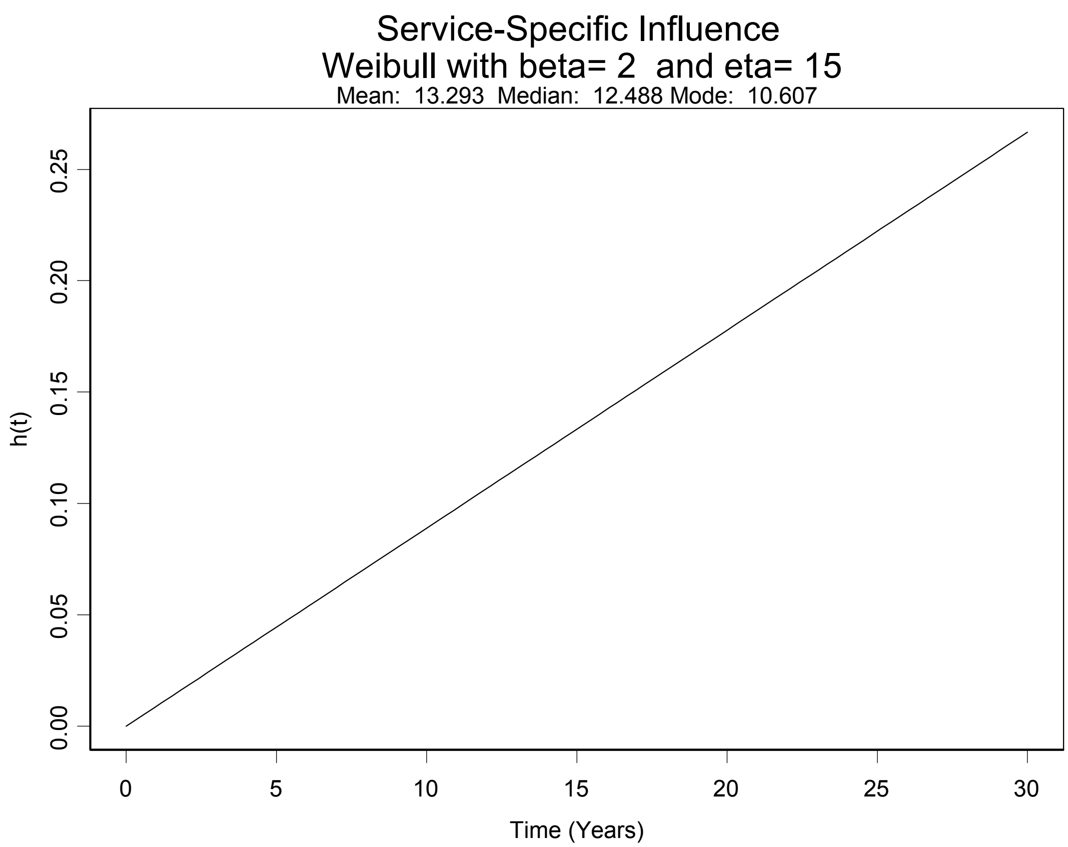

Figure 3-10. Graph of the Hazard Function for Obsolescence due to Service-Specific Influences

Figure 3-10 shows the model for obsolescence due to Service-specific influences. The risk of a weapon system that has not become obsolete due to another sub-type of obsolescence becoming obsolete specifically within any given Service is believed to increase at a fairly constant rate over time. In the absence of other sub-types forcing obsolescence, Service-specific obsolescence would likely be heavily influenced by the particular philosophies, roles, missions, and needs of each Service which uses the weapon system.

Different Services within the Department of Defense often look at their similar missions and weapon systems differently. The risk of obsolescence due to Service influence is zero at the beginning of a weapon system's life cycle, since Service acquisition decision-makers can safely be assumed to always purchase only weapon systems that are highly desired and thoroughly tested. However, I believe that the risk increases at approximately a constant rate as time progresses, and alternative weapon systems and functional demands occur. Note: that this form of obsolescence must be considered to be a subset of other sub-types; yet must be modeled separately due to historical evidence that all Services do not and will not declare weapon systems to be obsolete at the same rate or the same time. This sub-area is related to, but still fully independent of, both tactical and functional obsolescence, but differs from them in that as Service-Specific roles change, along with Service leadership philosophies, there is an ever-present risk of one or more Services feeling the need to influence divestment of a given weapon system, even while it still enjoys success within other Services. Such things as overall Operational Tempo (OPTEMPO), level of Defense Spending, and perceived level of likelihood of combat can also affect this area.

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IV. ANALYSIS OF MODEL OUTPUT

A. COMPETING FAILURE RATES[27]

Since we have defined operational obsolescence to be a function of many different sub-types of individual obsolescence, any weapon system may become obsolete due to more than one mode of obsolescence. One should take the view that the weapon system could have become operationally obsolete due to any one of the possible forms of obsolescence. By this view, the obsolescence forms "compete" as to which causes operational obsolescence for each particular weapon system. This can be viewed as a series system reliability model, with each obsolescence form comprising a block of the series system. Competing obsolescence forms analysis divides the analyses of obsolescence forms and then combines these results to provide an overall model for the weapon system under consideration. This methodology assumes statistical independence between the various sub-types of obsolescence, which is a strong, but necessary assumption, and is discussed in the following paragraphs. Until we have data, it is not feasible to either prove or disprove the independence assumption.

In order to begin analyzing data on weapon systems with more than one competing obsolescence form, we must perform a separate analysis for each sub-type of obsolescence. During each of these analyses, the point of obsolescence times for all other obsolescence forms not being analyzed are considered to be suspensions. This is necessary because the weapon system under analysis would have become obsolete, at some time in the future, due to the obsolescence form being analyzed, had the unrelated form not being analyzed not occurred. Thus in that case, the information available shows that the form under analysis did not occur and the weapon system under consideration accumulated valid time without becoming operationally obsolete due to the form under analysis or a suspension due to that form.

27 *Competing Failure Modes*, ReliaSoft Corporation, Tucson, AZ, 1996-2000, p.1.

Once the analysis for each separate obsolescence form has been completed, the resulting reliability equation for the weapon system due to all forms is the product of the reliability equation for each form, or:

(4.1) $R(t) = R_1(t) \cdot R_2(t) \cdot ... R_n(t)$

where n is the total number of obsolescence forms considered. This is the product rule for the reliability of series systems with statistically independent components, which states that the reliability for a series system is equal to the product of the reliability values of the components comprising the system. This causes the effect that the overall reliability of the weapon system is the minimum of the reliabilities based on the reliabilities of the sub-types. Thus, we find that reliabilities multiply; while hazard functions for each of the sub-types are additive.[28] Note that $R_i(t)$ is a reliability function that may be based on any assumed life distribution. In the production of this thesis the life distribution is the 2-parameter Weibull for all forms except Mission Change and Functional Obsolescence; and is the Lognormal for Mission Change, and the Logistic for Functional, sub-types of obsolescence. Any continuous life distribution can easily be used and would not affect the analytical techniques defined and illustrated in this thesis.

The equation for system reliability assumes that all the sub-types are statistically independent. At this point, I cannot be sure whether all the sub-types defined and examined are independent or not. Indeed, I suspect that there are serial dependencies among economic and logistical obsolescences, and potential colinearities among tactical, service-specific, and functional. I am making the simplifying assumption that all forms will behave independently for the purposes of this analysis. I feel that any errors induced will be small in magnitude, if they occur at all. Research into inter-dependencies between the sub-types of obsolescence is left as a topic for further study.

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28 William Q. Meeker and Luis A. Escobar, "Statistical Methods for Reliability Data," Wiley Series in Probability and Statistics, 1998, p. 116.

1. Bounds on Reliability[29]

The competing obsolescence forms reliability function is given by,

(4.2) $$\hat{R} = \prod_{i=1}^{n} \hat{R}_i$$

where,

$\hat{R}$ represents our estimate of the reliability,

$\hat{R}_i$ is the estimated reliability of the ith sub-type,

n is the total number of sub-types; eight in this thesis.

The upper and lower bounds on reliability are estimated using the logit transformation,

(4.3) $$R_U = \frac{\hat{R}}{\hat{R} + (1-\hat{R})\exp\left(-\frac{\kappa_\alpha \sqrt{Var(R)}}{R(1-R)}\right)}$$

and

(4.4) $$R_L = \frac{\hat{R}}{\hat{R} + (1-\hat{R})\exp\left(\frac{\kappa_\alpha \sqrt{Var(R)}}{R(1-R)}\right)}$$

κ_α is defined by,

(4.5) $$\alpha = \frac{1}{\sqrt{2\pi}} \int_{\kappa_\alpha}^{\infty} e^{-\frac{t^2}{2}} dt = 1 - \Phi(\kappa_\alpha)$$

If δ is the confidence level, then $\alpha = \frac{1-\delta}{2}$ for the two-sided bounds, and $\alpha = 1-\delta$ for the one-sided bounds.

29 *Competing Failure Modes*, ReliaSoft Corporation, Tucson, AZ, 1996-2000, p.5.

The variance of $\hat{R}$ is estimated by,[30]

(4.6) $$Var(\hat{R}) = \sum_{i=1}^{n} \left(\frac{\partial R}{\partial R_i} \right)^2 Var(\hat{R}_i) \text{, where}$$

(4.7) $$\frac{\partial R}{\partial R_i} = \prod_{j=1, j \neq i}^{n} \hat{R}_j$$

Thus,

(4.8) $$Var(\hat{R}) = \sum_{i=1}^{n} \left(\prod_{j=1, j \neq i}^{n} \hat{R}_j^2 \right) Var(\hat{R}_i)$$

(4.9) $$Var(\hat{R}_i) = \sum_{i=1}^{n} \left(\frac{\partial R_i}{\partial a_i} \right)^2 Var(\hat{a}_i)$$

where $\hat{\alpha}_i$ is an element of the model parameter vector. Therefore, the value of $Var(\hat{R}_i)$ is dependent on the underlying distribution. This procedure for the for the computation of the point estimate and estimated variance of reliability is known as the "delta method" or method of "statistical error propagation."[31] The delta method for estimating approximate expected values and variances of smooth non-linear functions of the parameters of models by linear functions of these same parameters is based on Taylor Series expansions of the functions. Additional detail on this method may be obtained by consulting Section 2 of Appendix B of Meeker and Escobar's "Statistical Methods for Reliability Data", 1998; Hahn and Shapiro, 1967, p. 228; or Stuart and Ord, 1994, p. 350.

For the Weibull distribution,

(4.10) $$Var(\hat{R}_i) = \left(\hat{R}_i e^{\hat{u}_i} \right)^2 Var(\hat{u}_i)$$

where,

(4.11) $$\hat{u}_i = \hat{\beta}_i \left(\ln(t - \hat{\gamma}_i) - \ln(\hat{\eta}_i) \right)$$

For the lognormal distribution,

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30 Ibid

31 William Q. Meeker and Luis A. Escobar, "Statistical Methods for Reliability Data," Wiley Series in Probability and Statistics, 1998, p. 619.

(4.12) $$Var(\hat{R}_i) = \left(f(\hat{z}_i) \cdot \hat{\sigma}' \right)^2 Var(\hat{z}_i)$$

where,

(4.13) $$\hat{z}_i = \frac{\ln(t) - \hat{\mu}_i'}{\hat{\sigma}_i'}$$

For the logistic distribution,

(4.14) $$Var(\hat{R}_i) = \left(f(\hat{z}_i) \cdot \hat{\sigma}' \right)^2 Var(\hat{z}_i)$$

where,

(4.15) $$\hat{z}_i = \frac{t - \hat{\mu}_i}{\hat{\sigma}_i}$$

These formulas give us the ability to calculate both a point estimate for the expected reliability of the weapon system and to establish desired confidence intervals for this estimate.

2. Bounds on Time[32]

The bounds on time are estimated by solving the reliability equation with respect to time, for all i = 1 to n sub-types of obsolescence. Mathematically:

(4.16) $$\hat{t} = \varphi(R, \hat{a}_i, \hat{b}_i)$$

(4.17) $$i = \overline{1, n}$$

where,

φ is the inverse function for the Reliability Equation,

for the Weibull distribution $\hat{a}_i$ is $\hat{\beta}_i$, and $\hat{b}_i$ is $\hat{\eta}_i$,

for the lognormal distribution $\hat{a}_i$ is $\hat{\mu}_i$, and $\hat{b}_i$ is $\hat{\sigma}_i$.

for the logistic distribution $\hat{a}_i$ is $\hat{\mu}_i$, and $\hat{b}_i$ is $\hat{\sigma}_i$.

Set,

(4.18) $$u = \ln(t)$$

32 Ibid, pp. 7-8.

The bounds on *u* are estimated from:

(4.19) $$u_U = \hat{u} + \kappa_\alpha \sqrt{Var(\hat{u})}$$

and,

(4.20) $$u_L = \hat{u} - \kappa_\alpha \sqrt{Var(\hat{u})}$$

Then the upper and lower bounds on time are found by using the equations,

(4.21) $$t_U = e^{u_U}$$

and,

(4.22) $$t_L = e^{u_L}$$

κ_α is calculated as before and Var($\hat{u}$) is computed as,

(4.23) $$Var(\hat{u}) = \sum_{i=1}^{n} \left(\left(\frac{\partial u}{\partial a_i} \right)^2 Var(\hat{a}_i) + \left(\frac{\partial u}{\partial b_i} \right)^2 Var(\hat{b}_i) + 2 \frac{\partial u}{\partial a_i} \frac{\partial u}{\partial b_i} Cov(\hat{a}_i, \hat{b}_i) \right)$$

As with the bounds on reliability, these formulas allow us to calculate a point estimate of the time when we expect a particularly modeled weapon system to become obsolete, as well as an estimated earliest time of obsolescence and latest time of obsolescence.

B. ANALYSIS OF MODEL OUTPUT

The analysis of the overall issue of operational obsolescence within this thesis was performed by combining the individual models of each of the sub-types of obsolescence into a grand model using the metric described above. The grand model was then run in a statistical software package known as BlockSim®, a product of the ReliaSoft Corporation, Tucson, AZ. The grand model output was graphed in three forms, described below to gain insights into how the weapon system could be expected to perform over time. The probability of obsolescence versus time and rate of system obsolescence versus time were assessed for understanding of how long we should expect a weapon system in a certain configuration to remain relevant before it would require modernization. Then I produced a third and final graph which showed the relative importance of each sub-type of obsolescence to the obsolescence rate of the weapon system to determine where design and modernization dollars should be invested to maximize the relevance period over the projected life cycle of the weapon system. Before showing example graphs, I will describe the methodology of producing the graphs and how information is obtained and interpreted from the graphs.

The first graph is Probability of Obsolescence versus Time. In this graph the model first calculates the point of near-certainty of system obsolescence in years and sets the upper endpoint of the x-axis to this value, scaling between 0 and this value in between. The y-axis is probability of obsolescence and is thus simply a linear scale from 0 to 1, or from 0% to 100%, as desired. The curve of the graph is monotonic increasing and shows the rate of growth of obsolescence probability along the time line from time 0 to the projected point of near-certainty of system obsolescence.

The second graph in each series is the Obsolescence Hazard versus Time. The x-axis in this graph is identical to the first graph. The y-axis is evenly scaled from 0 to the maximum rate at which the weapon system is becoming obsolete, as determined by the overall hazard function for the weapon system. The curve then shows how the obsolescence rate varies over time from time 0 until the point of system obsolescence. Time 0 is defined to be the point of initial fielding of the system or immediately following modernization.

The third graph, Reliability Importance versus Time, helps us determine where modernization dollars should be invested, or alternatively where to concentrate design effort to extend the time period before modernization is required. This graph has its x-axis scaled like the first two graphs, and its y-axis is scaled from 0 to 1. There is an individual curve for each sub-type of obsolescence. Each curve shows the partial derivative of the weapon system's reliability function with respect to the reliability function of the individual sub-type under consideration. That is:

(4.24) $$\text{Importance Value}_i = \frac{\partial R}{\partial R_i} = \prod_{j \neq i} R_j \, .$$

Notice that the Importance Value is the same value I used in equation 4.7 when I estimated the variance of the estimated value for the reliability of the system. This value plotted against time shows the influence of each sub-type of obsolescence on the overall decline in system reliability at any given point in time from time 0 until the system becomes obsolete, given the current model parameters. I conclude that the sub-type(s) with the greatest influence is the most important. I can then multiply each importance value by the relative cost per sub-type to realize an improvement in the reliability function for that sub-type in order to determine the sub-type with the greatest return on investment to help decide where to invest design or modernization dollars. That is, the change in reliability with respect to invested dollars is equal to the change in overall reliability with respect to changes in the reliability of each sub-type times the change in reliability of each sub-type with respect to dollars. In mathematical form:

$$\frac{\partial R}{\partial \$} = \frac{\partial R}{\partial R_i}\frac{\partial R_i}{\partial \$} \tag{4.25}$$

Unfortunately, $\frac{\partial R_i}{\partial \$}$ is often hard to estimate. It is known that for high levels of R_i, $\frac{\partial R_i}{\partial \$}$ is very small. Reliability is increasingly expensive as reliabilities of sub-types diminish.

1. Overall Reliability Model With a Typical Current Configuration

For the initial excursion I defined a typical weapon system as one modeled with each sub-type of obsolescence modeled with the distributions and parameters shown during model development in Chapter III. This represents no particular weapon system, but is considered a plausible representation of a typical weapon system with current design parameters. Table 4-1 shows the models and parameters chosen to represent each sub-type of obsolescence.

Sub-type of Obsolescence (O_i)	Model	Shape Parameter	Scale Parameter
i = :			
1. Tactical	Weibull	3	20
2. Logistical	Weibull	3	1.5
3. Economic	Weibull	3	15
4. Functional	Logistic[33]	3.08	10
5. Technological	Weibull	3.5	16
6. Political	Weibull	1	15
7. Mission Change	Lognormal	2.5	1.2
8. Service Specific	Weibull	2	15

Table 4-1. Table of Distribution Models and Parameters of Sub-types of Obsolescence

Table 4-1 summarizes the life cycle distributions and parameters used to model each of the sub-types of obsolescence. These are discussed in detail in the text of Chapter III of this thesis.

[33] Due to a limitation in BlockSim®, the Normal distribution was used to represent the Logistic distribution in the overall model, owing to the similarity of these two distributions. See Appendix A, Section A.3. for a more detailed description.

a. Probability of Obsolescence versus Time

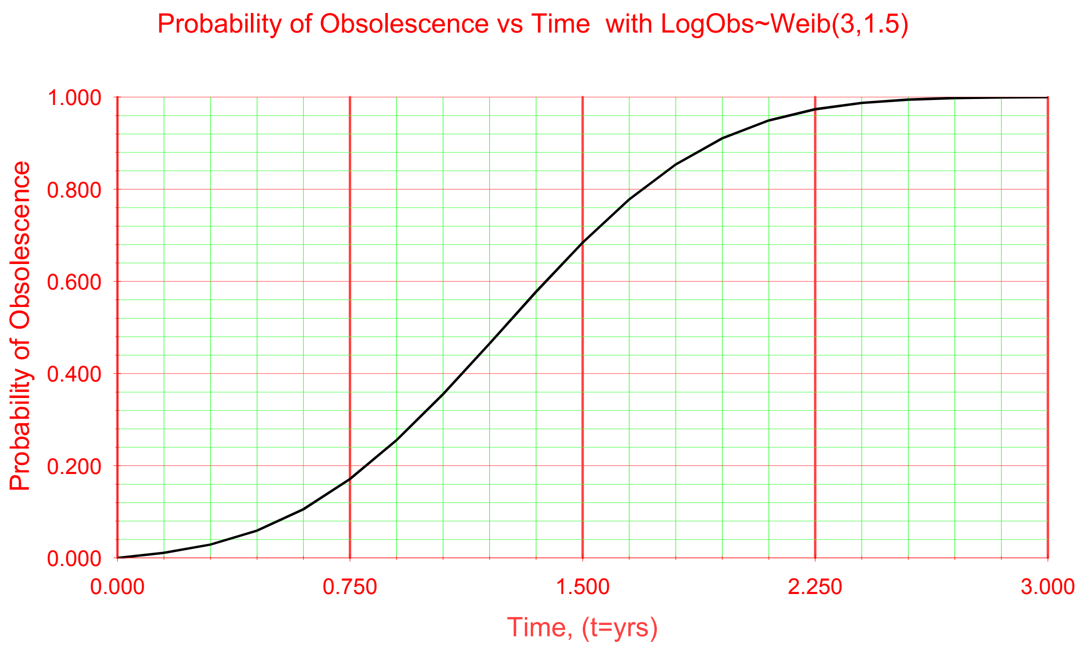

Figure 4-1. Graph of the Probability of Obsolescence versus Time for Current Configuration

Figure 4-1 shows that the probability of obsolescence increases at an increasing rate for approximately the first 1.05 years; increases at a relatively linear rate for the next 0.6 years, and then increases at a decreasing rate until the system is assured of becoming obsolete approximately 2.55 years after fielding. Logistical obsolescence dominates the model with the parameters believed to represent current systems. The expected time to obsolescence for this weapon system is 1.25 years; with a median obsolescence time of 1.24 years.

b. Obsolescence Rate versus Time

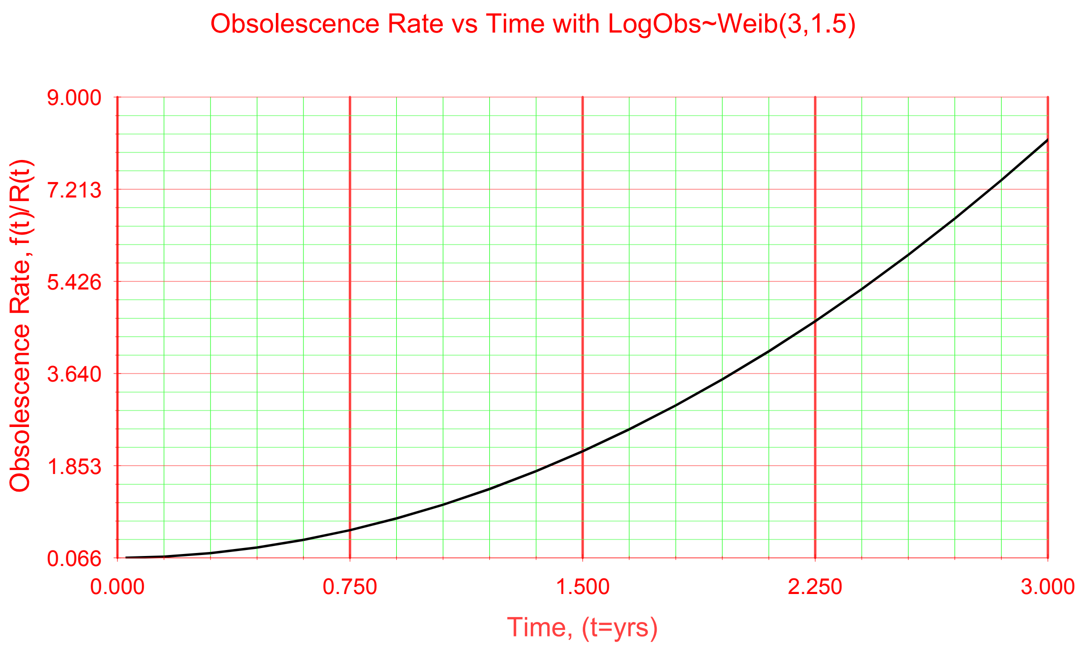

Figure 4-2. Graph of the Obsolescence Rate versus Time for Current Configuration

Figure 4-2 shows that the rate of obsolescence is concave upwards.

c. Reliability Importance versus Time

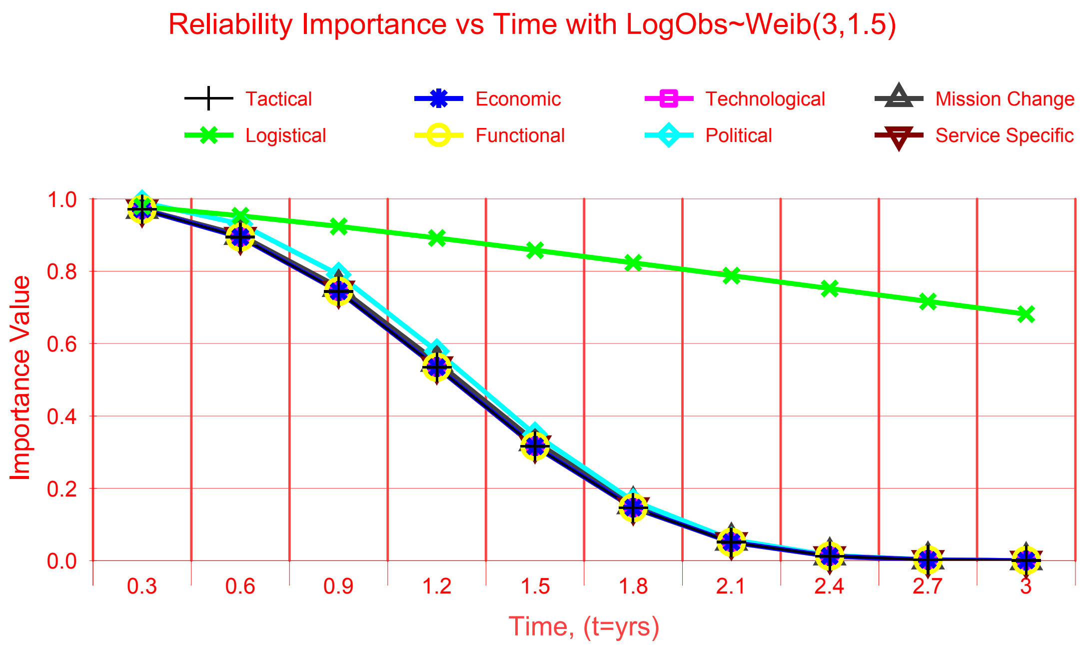

Figure 4-3. Graph of the Reliability Importance versus Time for Current Configuration

Figure 4-3 shows that Logistical obsolescence is dominating all other sub-types of obsolescence by a large margin. Thus, we conclude that it is much more important, and potentially valuable, to resolve logistical obsolescence under current conditions than to invest in improvements in any other sub-forms of obsolescence. We will have a complete picture of this once actual system reliability and cost data are available.

2. Overall Reliability With Phase I Improvements

To demonstrate the analytical approach used and the value of the model, I now propose Phase I of a conceptual Product Improvement Program (PIP). During this phase of the PIP, we will improve the timeline of component development, fielding the most technologically superior parts and components that have demonstrated adequate reliability for the designed weapon system. As described in Chapter III, I postulate that reasonable expectations for this "just in time fielding" practice under Moore's Law assumptions gives us a four-fold increase in the scale parameter of the logistical obsolescence model, where we determined in the last excursion that our efforts should be concentrated.

a. Probability of Obsolescence versus Time

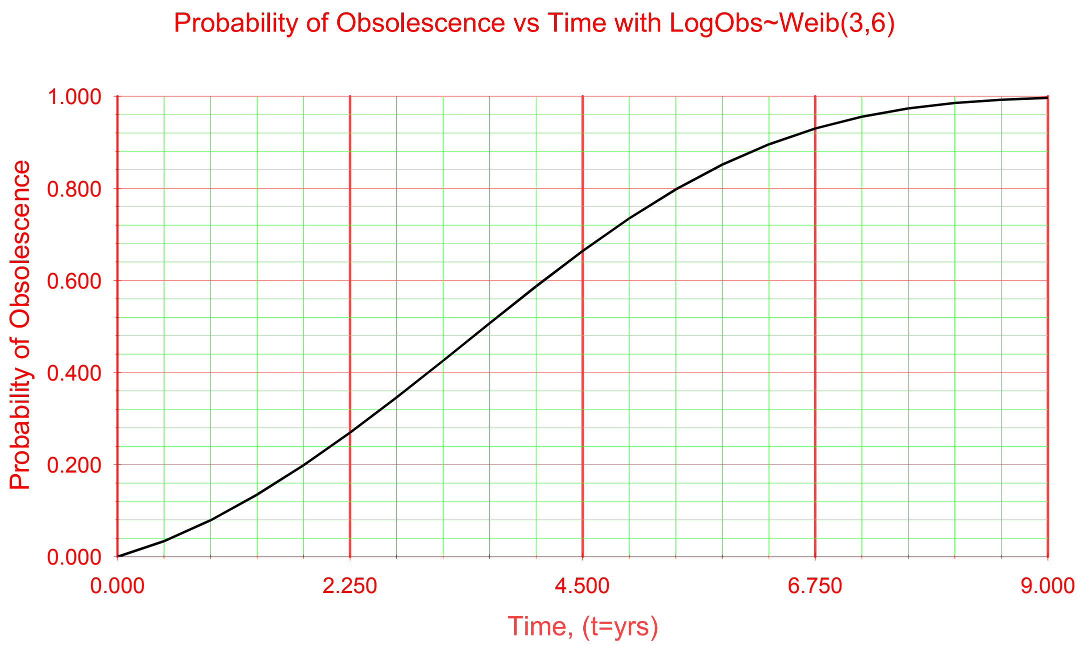

Figure 4-4. Graph of the Probability of Obsolescence versus Time with Phase I Improvements

The shape and general behavior of the graph are the same as in excursion one, but a four-fold increase in the scale parameter of the logistical obsolescence model translates to a four-fold scaling of the x-axis. The mean time to obsolescence for this improved weapon system design structure is 3.66 years; with a median time to obsolescence of 3.64 years.

b. Obsolescence Rate versus Time

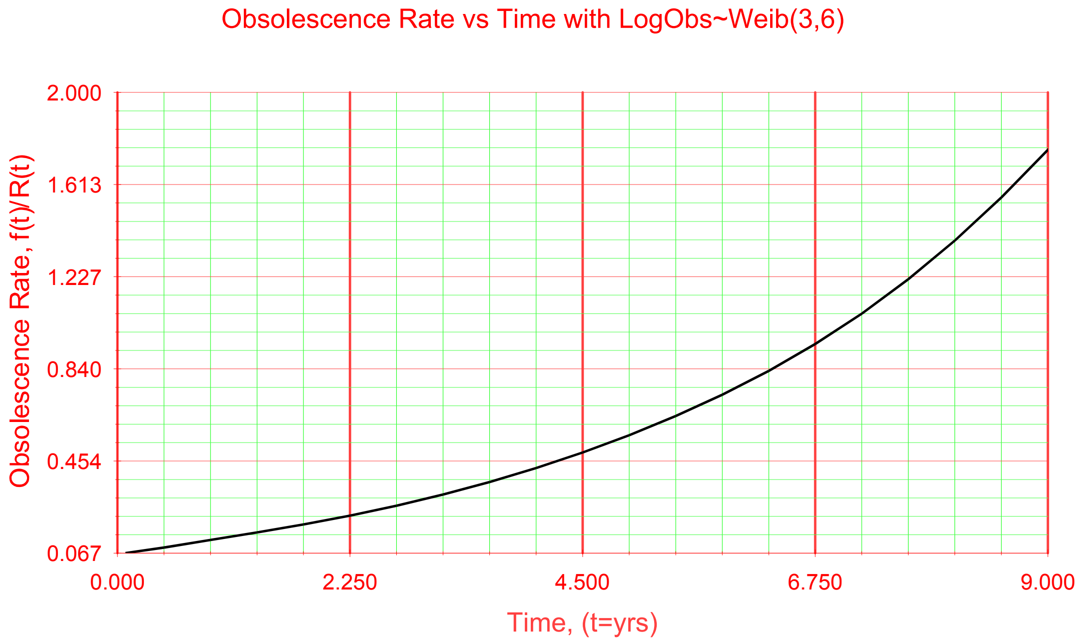

Figure 4-5. Graph of the Obsolescence Rate versus Time with Phase I Improvements

As in Figure 4-4, we continue to see improvement in the reliability of the modeled weapon system. A four-fold increase in the scale parameter of logistical obsolescence decreases the rate of system obsolescence by approximately four, with a corresponding increase in the expected time to system obsolescence. Thus, the application of a smarter fielding methodology, that of purchasing the most technology advanced electronic components that have proven reliable and applicable as close to commencement of production as possible; and purchasing sufficient quantities of the components to complete production and support of all vehicles in the MY contract; with relatively little, if any, direct increase in fielding cost, has paid large benefits in system reliability gains.

c. *Reliability Importance versus Time*

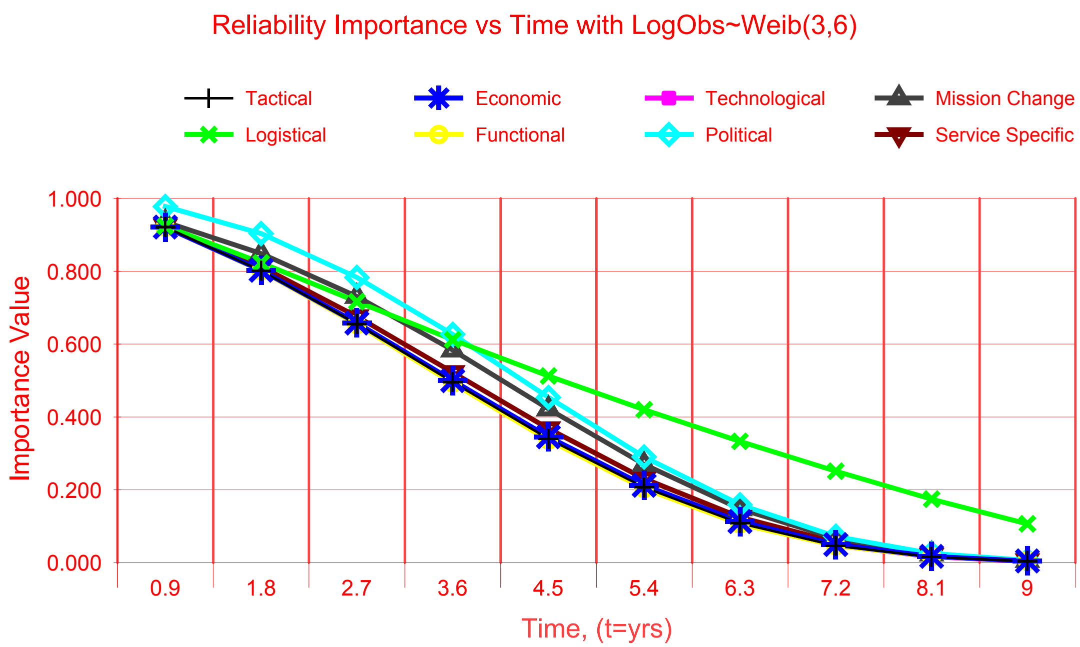

Figure 4-6. Graph of the Reliability Importance versus Time with Phase I Improvements

Improvements to the logistical reliability of the weapon system cause other sub-types to be more influential during the first few years following fielding or major modernization, when the probability of system obsolescence is relatively low overall. However, after approximately three and a half years, logistical obsolescence again dominates the model, and continues to do so until the system eventually reaches the point of obsolescence. I conclude from this that investment in logistical relevance has paid off, and that this is still the likely area where we should concentrate our next phase of effort. Note that the most important sub-type in the early years of the systems life is now political obsolescence, which is non-addressable with modernization money.

3. Overall Reliability With Phase II Improvements

As a final demonstration of the value of using the models and methods developed and presented in this thesis, I propose as Phase II of the PIP that by investing significant resources into the most important current sub-type of obsolescence, logistical in this example, to optimize open architecture design with all contractors committing to develop future components that maintain form, fit, and function with the fielded design it is possible to realize modernization through spares. This realization would essentially cause logistical obsolescence to become non-applicable as a driving force towards overall system obsolescence since we would be able to keep the weapon system logistically relevant throughout its life cycle. It is not currently possible to prove that this methodology would produce results as optimal as those postulated, but these results are presented to demonstrate the potential value of the model and analytical methods for use in the future.

a. Probability of Obsolescence versus Time

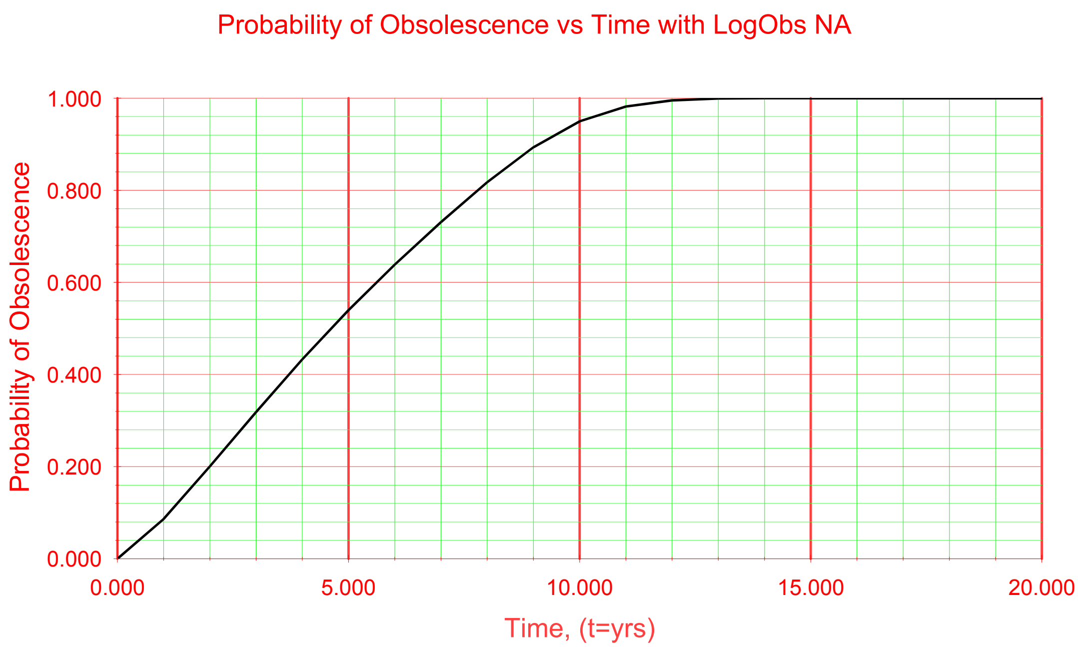

Figure 4-7. Graph of the Probability of Obsolescence versus Time with Phase II Improvements

Figure 4-7 shows that with logistical obsolescence removed the probability of obsolescence is fairly linear over time until approximately nine years at which time the probability of obsolescence increases at a decreasing rate until the hypothetical weapon system reaches the point of near-certain obsolescence. The mean time to obsolescence with this system design is 4.76 years; with a median time to obsolescence of 4.69 years.

b. Obsolescence Rate versus Time

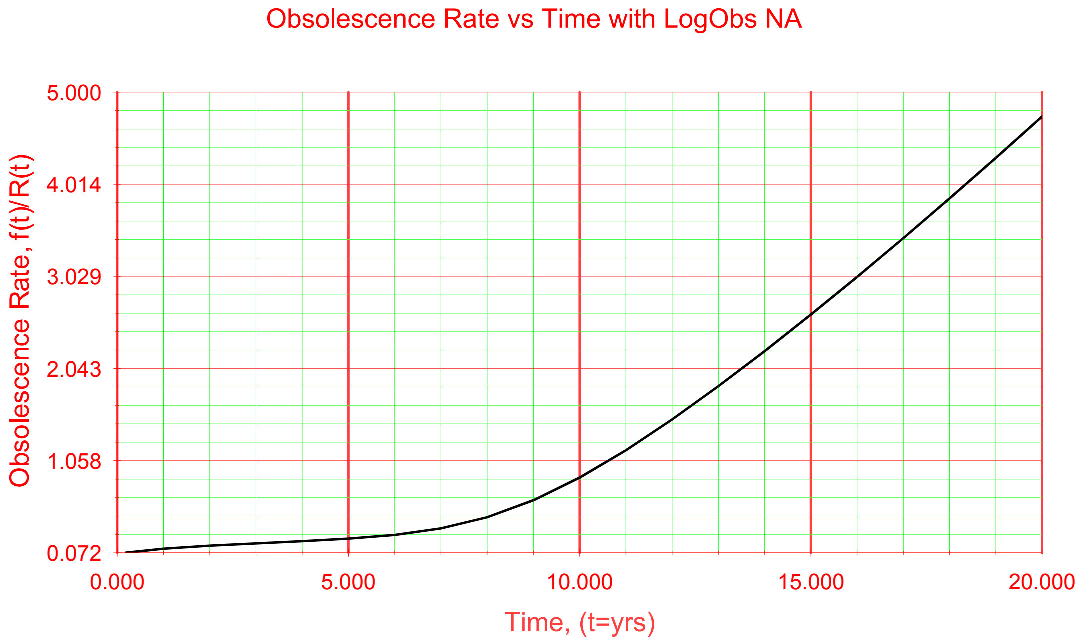

Figure 4-8. Graph of the Obsolescence Rate versus Time with Phase II Improvements

Figure 4-8 shows that the rate of obsolescence with logistical obsolescence removed is relatively low for at least the first six years. Following this period, the rate increases at a slowly increasing rate until the system becomes obsolete due to other influences, or is modernized.

c. *Reliability Importance versus Time*

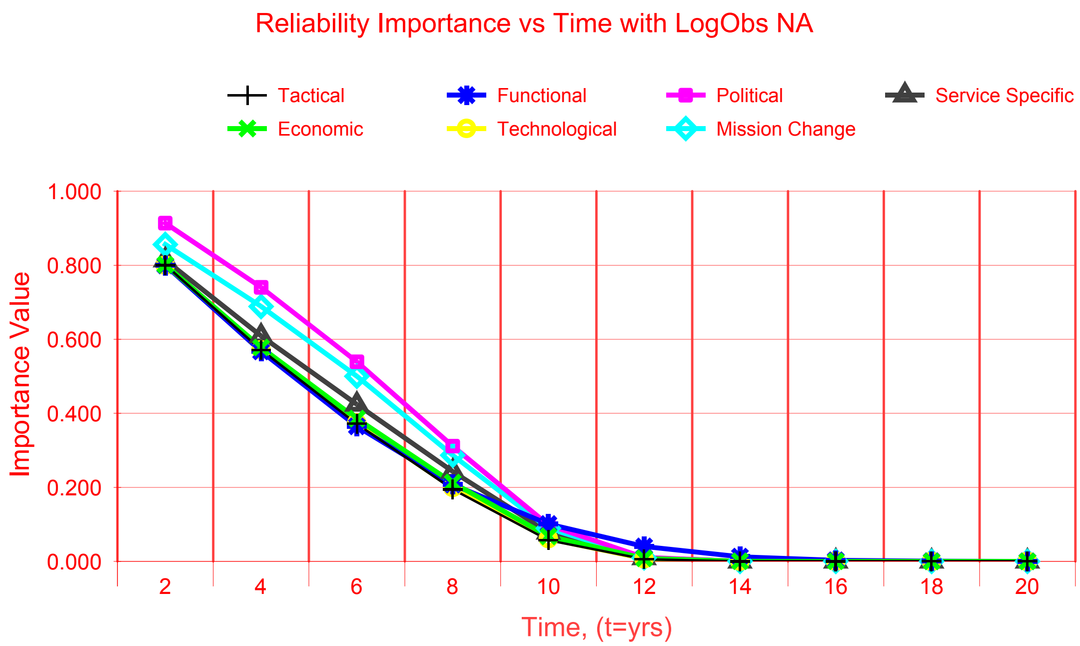

Figure 4-9. Graph of the Reliability Importance versus Time with Phase II Improvements

In Figure 4-9 we see that by determining and fixing our most important cause(s) of obsolescence we may succeed at eliminating the dominant forces driving our systems to obsolescence. The influences on system reliability are relatively equal and manageable, particularly beyond the point where the probability of system obsolescence is high, between the remaining sub-types of obsolescence. The dominant forms in the first ten years of the weapon system's life cycle are political and mission change. We cannot fix political obsolescence through monetary investment. Mission change obsolescence requires modernization or a deliberate decision to accept a certain degree of obsolescence with the weapon system as is. At this point there is no obvious single controllable source of system obsolescence.

This concludes the analysis of the models developed in this thesis. For the hypothetical typical weapon system, logistical obsolescence was the dominant sub-type. Therefore, I invested resources to solve the problems associated with logistical obsolescence of my system. This same approach can be used successfully on any real weapon system for which we have reliability data that we can use to estimate the required parameters for the models.

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS FROM MODELS

I have developed the first working definition for the troubling phenomenon of operational obsolescence. I propose that this definition be accepted by and incorporated into the vocabulary of the U.S. Army Acquisition Corps, as well as the Army community. The definition may need to be refined and evolved over time. Nevertheless, the definition within this thesis gives us a common starting point from which to continue to study, discuss, and remediate the problem of operational obsolescence of our weapon systems. This thesis demonstrates that the overarching concept of operational obsolescence of any particular weapon system actually rests on eight obsolescence pillars, comprised of the eight sub-types of obsolescence defined and developed within this thesis. Each of these sub-types has been modeled individually and plausible distributions and parameters are presented for each of these "feeders" of the overall obsolescence model for any weapon system. Under the assumption of statistical independence of the sub-types of obsolescence, I have developed and demonstrated the overall or grand model for weapon system obsolescence by showing that hazard functions are additive and thus the overall reliability model is the product of the reliability functions of each of the sub-types of obsolescence.

In order to obtain maximum value from this research effort, we must have data. No single weapon system or group of weapon systems can adequately represent the full spectrum of issues that we must examine to fully understand and address operational obsolescence. Accordingly, the U.S. Army Materiel Systems Analysis Activity (AMSAA) or other similar agency should develop a reference database containing the timelines and estimated parameters needed for the models developed in this thesis. To be accurate and useful the database would have to cover dozens or even hundreds of representative weapon systems with inputs obtained over decades. Therefore, I recommend that a separate research effort be performed to obtain this data. The research would either have to be collected for many years into the future, or better, criteria developed for when historical weapon systems became obsolete for each of the eight sub-types developed in my thesis, and a database assembled from historical data over the past forty to fifty years.

Once data are available and parameters are estimated for the models developed, these models will show the distribution and time to obsolescence for any weapon system under study, as well as the dominant and contributing sources for that obsolescence. Using graphs similar to those used in Chapter IV for analysis of the output from my models, it is possible for acquisition and support personnel to find the areas of concern for any production and support scheme devised for a weapon system. From this point, it is a straightforward process to develop courses of action necessary to detect and delay or prevent obsolescence of a weapon system, which can now be done in an informed and organized fashion. We can delay or prevent obsolescence by directly attacking the type and source of obsolescence most influential in driving the system to obsolescence.

This thesis cannot prevent our weapon systems from becoming obsolete. However, now that relationships and timelines can be estimated, we can scientifically approach the problem of operational obsolescence. I conclude from the information currently available and based on my expert opinion that we should make our initial attacks on the issue of logistical obsolescence, particularly as we field increasing technologically advanced systems that rely heavily on electronic components. I recommend striving to develop a methodology that allows continuous refreshment of components over the life cycle of the weapon system through spares replacement, which can be continuously upgraded and modernized by our contractors. This gives both the Army and industry the most competitive and capable environment in which to work and perform our mutually supportive and mutually dependent missions.

B. RECOMMENDATIONS FOR FUTURE RESEARCHERS

The life cycle of any weapon system commences not when the system is fielded, but from the moment that concept development commences. Accordingly, our attack on obsolescence of any particular weapon system begins at the stage of conceptualization and initial design. A better-designed weapon system is more robust with regard to obsolescence avoidance. I did not perform any specific research on the impact of the

Department of Defense's current efforts into Force Transformation, or the magnitude of the impact of the current pace of technology on acquisition cycles. Nevertheless, it seems logical that these contemporary phenomena are significantly shortening the timeline for weapon system acquisition. Accordingly, I recommend future study into the impact of accelerated procurement of evolving technology on weapons system obsolescence.

There appears to be at least one major gain and at least one major concern that will occur with substantially shortened acquisition cycles. In the past, we have often spent more than a decade to design, test, and field weapon systems. This may have to be reduced to a period of three to five years in order to avoid the issues of logistical and technological obsolescence from the very time that the system is first fielded. We are not sure about this conclusion at this point. Given that this may be a plausible requirement, such a shortened acquisition timeline will tend to give our weapon systems the advantage of automatically containing newer technologies, which will demonstrate gains in the areas of logistical, economic, and technological obsolescence. On the other hand, we must be cautious that as we shorten acquisition cycles we do not allow any degradation of standards in the engineering and testing of our weapons systems, which would lead to logistical and reliability problems after the weapons system is fielded. This is an area that appears fertile for future research and examination.

There are still many other questions that we must answer in an attempt to identify and combat operational obsolescence. It was not feasible to answer all of the germane questions in a single thesis. This thesis demonstrates how to solve many of these problems once data are collected and can be input into the models. Other issues will require additional research. My thesis sponsor, the Longbow Apache Project Manager, presented a number of the issues that follow as pertinent questions in the examination of operational obsolescence. Among the most important of the remaining issues are the following:

- Do we really need the most modern technologies to meet our National Defense objectives?
- How much does it cost to implement one modernization plan versus another?
- What are the chances that a truly revolutionary technological advancement will occur before we can fully reap the benefits of fielding a new system?

For example, an Aeronautical Engineering breakthrough that makes the use of rotary–wing aircraft impractical

- If such a technology exists, how long will it take to mature and implement it?
- Even if a new system is somewhat better than an existing system, from a Cost/Benefit perspective, do its acquisition and support costs justify its fielding versus the capabilities of current systems?
- How accurately can we make our predictions concerning the relevance of a specific aircraft given a prescribed modernization plan?
- Does the pace of technology cause existing systems to become operationally obsolete faster or slower than systems did in the past?
- How much defensive, economic or moral value is there to continuing to modernize existing systems versus fielding new systems?
- When we upgrade a current weapon system or its components for purely sustainment reasons, can we simultaneously gain a performance increase as a collateral benefit simply due to technological advances since the original system was designed?
- What are the costs to gain added reliability in each sub-area of obsolescence for given types of weapon systems?
- How does the weapon system actually improve with changes in reliability?
- If we intend to modernize an existing weapon system at a future date, what are the costs associated with closing the current production line and then reopening it when the modernization effort commences?
- For how long would it be more economically-feasible for the Army to pay the costs of maintaining a "warm production base" versus restarting a shut-down production line?

Although there are still many questions that must be answered, I feel that through application of the techniques demonstrated in this thesis, we can make substantial improvements in our ongoing effort to minimize or eliminate operational obsolescence of our weapon systems. This is a new area of study and much remains to be done. By application of the scientific method, the military forces of the United States and our tremendous industrial base can be jointly mobilized to produce an ever increasingly relevant and ready force, transformed, and prepared for the twenty-first century and beyond.

APPENDIX A. BACKGROUND ON MODELS AND DISTRIBUTIONS

A. LOCATION-SCALE DISTRIBUTIONS[34]

As described in Chapter III, each of the sub-models and the resulting overall model are hazard function models derived from continuous distributions. All of the distributions used further fall under the grouping of what is known as Location-Scale Distributions; hence the use of the one parameter to set the basic shape of the distribution and another to set the scale of the particular distribution.

Any random variable, *X*, is said to belong to the location-scale family of distributions if its cumulative distribution function (cdf) can be expressed as:

(A.1) $$\Pr(X \le x) = F(x; \mu, \sigma) = \Phi\left(\frac{x-\mu}{\sigma}\right),$$

where Φ does not depend on any unknown parameters. In such a case, we say that $-\infty < \mu < \infty$ is a location parameter and that $\sigma > 0$ is a scale parameter. Upon substitution, we see that Φ is the cdf of X when $\mu = 0$ and $\sigma = 1$. Location-scale distributions are important for a number of reasons, including, but not limited to:

- Many of the widely used statistical distributions are either location-scale distributions or closely related to them. These distributions include the exponential, normal, Weibull, lognormal, loglogistic, logistic, and extreme value distributions.
- Methods for data analysis and inference, statistical theory, and computer software developed for the location-scale family can be applied to any of the members of the family.
- Theory for the location-scale distributions is relatively simple.

In cases where Φ does depend on one or more unknown parameters, X is not a member of the location-scale family, but the location-scale structure and notation will still be useful.

34 Wallace R. Blischke and D.N. Prabhakar Murthy, "Reliability Modeling, Prediction and Optimization," Wiley Series in Probability and Statistics, 2000, pp. 78-79.

A random variable *Y* belongs to the log-location-scale family of distributions if *X* = log(*Y*) is a member of the location-scale family. The Weibull, lognormal, and loglogistic distributions are the most important members of this family; the logistic distribution is a member of the location-scale family.

1. Weibull Distribution[35]

The Weibull distribution cdf is generally written as:

(A.2) $$\Pr(T \le t; \eta, \beta) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], t > 0 .$$

For this parameterization, $\beta > 0$ is a shape parameter and $\eta > 0$ is a scale parameter as well as being the 0.632 quantile. The practical value of the Weibull distribution stems from its ability to describe virtually all failure distributions, with many different commonly occurring shapes. When $0 < \beta < 1$, the Weibull has a decreasing hazard function. When $\beta > 1$, the Weibull has an increasing hazard function. At precisely $\beta = 1$, the Weibull describes the exponential distribution.

For any integer m > 0,

(A.3) $$E(T^m) = \eta^m \Gamma(1 + m/\beta) ,$$

where,

(A.4) $$\Gamma(\kappa) = \int_0^\infty z^{\kappa - 1} \exp(-z) dz$$

is the gamma function. From this we can see that the mean and variance of the Weibull distribution are:

(A.5) $$E(T) = \eta\Gamma(1 + 1/\beta)$$

and

(A.6) $$Var(T) = \eta^2[\Gamma(1 + 2/\beta) - \Gamma^2(1 + 1/\beta)].$$

The Weibull *p*-quantile is:

(A.7) $$t_p = \eta[-\log(1 - p)]^{1/\beta}.$$

35 Ibid, pp. 85-86.

Note that when β = 1, the cdf reduces to the exponential distribution with scale parameter $\theta = \eta$.

The relationship of the Weibull distribution to the location-scale family of distributions is found in the relationship between the Weibull and the Smallest Extreme Value distribution. If T has a Weibull distribution, then $Y = \log(T) \sim SEV(\mu, \sigma)$, where $\sigma = 1/\beta$ is the scale parameter, and $\mu = \log(\eta)$ is the location parameter. The Weibull-SEV relationship parallels the Lognormal-Normal relationship. The SEV parameterization is often more convenient because location-scale distributions are easier to work with in general. More detail on the SEV distribution can be found in Meeker and Escobar, 1998, pp. 83-85.

The use of the Weibull distribution is often justified due to its ability to model failure-time data with either decreasing or increasing hazard functions. Note that the Weibull described above is the two-parameter Weibull, as opposed to the three-parameter Weibull, which includes a translation parameter, γ. Only the two-parameter Weibull was used in the production of this thesis.

2. Lognormal Distribution[36]

When T has a lognormal distribution, we show this by $T \sim$ LOGNOR(μ,σ). If T ~ LOGNOR(μ,σ), then $X = \log(T) \sim$ NOR(μ,σ). This relationship is the justification for the use of the lognormal in distributions of the location-scale family. The lognormal cdf and pdf are:

(A.8)
$$F(t;\mu,\sigma) = \Phi_{nor}\left[\frac{\log(t)-\mu}{\sigma}\right],$$

and

(A.9)
$$f(t;\mu,\sigma) = \frac{1}{\sigma t}\phi_{nor}\left[\frac{\log(t)-\mu}{\sigma}\right], t > 0,$$

36 Ibid, pp. 82-83.

where ϕ_{nor} and Φ_{nor} are the pdf and cdf for the standardized normal. The median, $t_{.5}$ = exp(μ) is a scale parameter and σ > 0 is a shape parameter.

The most common definition of the lognormal distribution uses base *e*, the natural, logarithms. The definition of the parameters μ, the mean of the logarithm of T, and σ, the standard deviation of the logarithm of T, will depend on the base used. For this reason, it is important to be consistent in the base used.

For any integer m >0:

(A.10) $$E(T^m) = \exp(m\mu + m^2\sigma^2/2)$$

It follows from this that the mean and variance of the lognormal distribution are:

(A.11) $$E(T)=\exp(\mu + 0.5\sigma^2)$$

and

(A.12) $$Var(T) = \exp(2\mu + \sigma^2)[\exp(\sigma^2) - 1],$$ respectively.

The quantile function of the lognormal distribution is:

(A.13) $$t_p = \exp[\mu + \Phi_{nor}^{-1}(p)\sigma].$$

The lognormal distribution is a common model for failure times. Following from the Central Limit Theorem, application of the lognormal distribution could be justified for a random variable that arises from the product of a number of identically distributed and independent positive random quantiles. It has been suggested that the lognormal is an appropriate model for time to failure caused by a degradation process with combinations of random rate constants that combine multiplicatively. The lognormal distribution is widely used to describe time to failure from fatigue crack growth in metals.[37] The lognormal hazard function starts at 0, increases to some point in time, and then decreases, eventually to 0. For σ large, the hazard function reaches a maximum early and then decreases. For this reason, the lognormal distribution is often used as a model for a population of electronic components that exhibits a decreasing hazard function. It has been suggested that early-life "hardening" of certain kinds of materials or components might lead to such a hazard function. The lognormal distribution also arises

[37] Ibid, p. 83.

as the time to failure distribution of certain degradation processes. The lognormal distribution shown here is the two-parameter distribution, as opposed to the three-parameter, which includes a translation parameter, similar to the three-parameter Weibull, but which was not used in the production of this thesis.

3. Logistic Distribution[38]

When X has a logistic distribution, we show this by $X \sim \text{LOGIS}(\mu, \sigma)$. The logistic distribution is a location-scale distribution with cdf, pdf, and hf:

(A.14) $$F(x;\mu,\sigma) = \Phi_{\text{logis}}\left(\frac{x-\mu}{\sigma}\right),$$

(A.15) $$f(x;\mu,\sigma) = \frac{1}{\sigma}\phi_{\text{logis}}\left(\frac{x-\mu}{\sigma}\right),$$

(A.16) $$h(x;\mu,\sigma) = \frac{1}{\sigma}\Phi_{\text{logis}}\left(\frac{x-\mu}{\sigma}\right), -\infty < x < \infty,$$

where $\Phi_{\text{logis}}(z) = \exp(z)/[1 + \exp(z)]$ and $\phi_{\text{logis}}(z) = \exp(z)/[1 + \exp(z)]^2$ are the cdf and pdf, respectively for a standardized LOGIS, with $\mu = 0$, and $\sigma = 1$. Here $-\infty < \mu < \infty$ is a location parameter and $\sigma > 0$ is a scale parameter.

For any integer m > 0:

(A.17) $$E\left[(X-\mu)^m\right] = 0$$

if m is odd, and

(A.18) $$E\left[(X-\mu)^m\right] = 2\sigma^m (m!)\left[1-\left(\frac{1}{2}\right)^{m-1}\right]\sum_{i=1}^{\infty}\left(\frac{1}{i}\right)^m$$

if m is even. From this:

(A.19) $$E(X) = \mu$$

and

(A.20) $$\text{Var(X)}=\frac{\sigma^2\pi^2}{3}$$

The p quantile is:

38 Ibid, pp. 88-89.

(A1.21) $$t_p = \mu + \Phi^{-1}_{\text{logis}}(p)\sigma,$$
where,

(A1.22) $$\Phi^{-1}_{\text{logis}}(p) = \log\left[p/(1-p)\right]$$

is the p quantile of the standard logistic distribution.

The shape of the logistic distribution is very similar to that of the normal distribution; the logistic distribution has slightly "longer tails." Indeed, it would require an extremely large number of observations to assess whether data came from a normal or logistic distribution.[39] Because of this similarity, the Normal distribution, with appropriate parameters, was used in the BlockSim® model to represent the Logistic distribution. BlockSim® did not allow the use of the Logistic distribution. The main difference between the distributions is in the behavior of the hazard function in the upper tail of the distribution, where the logistic hf levels off, approaching $1/\sigma$ for large x. This is the reason I chose to use the logistic distribution to model the hazard function for functional obsolescence. For certain purposes, the logistic distribution is preferred to the normal because its cdf can be written in a simple closed form. With modern software, however, it is not any more difficult to compute probabilities from a normal cdf.

B. PRODUCTION OF HAZARD FUNCTION GRAPHS

The hazard function graphs for each of the sub-types of operational obsolescence displayed in Chapter III are produced from the following S-Plus 2000® functions for the Weibull; Lognormal; and Logistic distributions, respectively.[40]

1. Graph of the Weibull Hazard Function

```
function(beta, eta, xlim = 100, n = 100)
# This function calculates and plots the Hazard Function of the Weibull Distribution based on
# user input parameters.
{
```

39 Ibid, p. 89.

40 The assistance of Professor Samuel Buttrey in the production of these S-Plus® functions is gratefully acknowledged.

```
        x <- seq(1e-009, xlim, length = n)
        one.minus.p <- 1 - pweibull(x, shape = beta, scale = eta)
        y <- dweibull(x, shape = beta, scale = eta)/one.minus.p
        thresh <- 1e-009
        weibmean <- eta * gamma((1/beta) + 1)
        weibmedian <- eta * ((log(2))^(1/beta))
        weibmode <- eta * ((1 - (1/beta))^(1/beta))
        if(any(one.minus.p < thresh)) {
                warning(paste("Deleted", sum(one.minus.p < thresh),
                        "points"))
                x <- x[one.minus.p >= thresh]
                y <- y[one.minus.p >= thresh]
        }
        plot(x, y, type = "l", main = paste("Weibull with beta=",
                beta, " and eta=", eta), xlab = "Time (Years)",
                ylab = "h(t)")
        mtext(paste("Mean: ", signif(weibmean, 5), " Median: ",
                signif(weibmedian, 5), "Mode: ", signif(weibmode, 5
                )))
}
```

Figure A-1. Hazard Function based on the Weibull Distribution

Figure A-1 gives the S-Plus® code for the production of the hazard function distribution, including its graph, for any model based on the Weibull Distribution with the user providing estimated parameters in the call statement to the function. Any modern statistical package could produce the graph and hazard function distribution following the example of the code found in the figure.

2. Graph of the Lognormal Hazard Function

```
function(mu, sigma, xlim = 100, ylim = 10, n = 100)
# This function calculates and plots the Hazard Function of the Lognormal Distribution based on # user input parameters.
{
        x <- seq(1e-009, xlim, length = n)
        one.minus.p <- 1 - plnorm(x, meanlog = mu, sdlog = sigma)
        y <- dlnorm(x, meanlog = mu, sdlog = sigma)/one.minus.p
        thresh <- 1e-009
        lognormmean <- exp((mu + (sigma^2)/2))
        if(any(one.minus.p < thresh)) {
                warning(paste("Deleted", sum(one.minus.p < thresh),
                        "points"))
                x <- x[one.minus.p >= thresh]
                y <- y[one.minus.p >= thresh]
        }
```

```
        plot(x, y, type = "l", main = paste("Lognormal with mu=",
              mu, " and sigma=", sigma), xlab = "Time (Years)",
              ylab = "h(t)", ylim = c(0, ylim))
        mtext(paste("Mean: ", signif(lognormmean, 5)))
}
```

Figure A-2. Hazard Function based on the Lognormal Distribution

Figure A-2 gives the S-Plus® code for producing the hazard function distribution and resulting graph for any model based on the Lognormal Distribution with the user providing estimated parameters in the call statement to the function. Any modern statistical package could produce the graph and hazard function distribution following the example of the code found in the figure.

3. Graph of the Logistic Hazard Function

```
      function(mu, sigma, xlim = 100, ylim = 10, n = 100)
      # This function calculates and plots the Hazard Function of the
Logistic        # Distribution based on user input parameters.
      {
            x <- seq(1e-009, xlim, length = n)
            one.minus.p <- 1 - plogis(x, location = mu, scale = sigma)
            y <- dlogis(x, location = mu, scale = sigma)/one.minus.p
            thresh <- 1e-009
            logisticmean <- mu
            logisticvar <- sigma^2 * (pi^2/3)
            if(any(one.minus.p < thresh)) {
                  warning(paste("Deleted", sum(one.minus.p < thresh),
                        "points"))
                  x <- x[one.minus.p >= thresh]
                  y <- y[one.minus.p >= thresh]
            }
            plot(x, y, type = "l", main = paste("Logistic with mu=",
                  mu, " and sigma=", sigma), xlab = "Time (Years)",
                  ylab = "h(t)", ylim = c(0, ylim))
            mtext(paste("Mean: ", signif(logisticmean, 5),
                  "   Variance:  ", signif(logisticvar, 5)))
      }
```

Figure A-3. Hazard Function based on the Logistic Distribution

Figure A-3 gives the S-Plus® code for producing the hazard function distribution and resulting graph for any model based on the Logistic Distribution with the user providing estimated parameters in the call statement to the function. Any modern statistical package could produce the graph and hazard function distribution following the example of the code found in the figure.

APPENDIX B. LIST OF ACRONYMS AND DEFINITIONS

AMSAA – Army Materiel Systems Analysis Activity

CDF – Cumulative Distribution Function

DMS – Diminishing Manufacturing Sources

FCS – Future Combat System

HF – Hazard Function

IOC - Initial Operational Capability

LHA – Light Helicopter Amphibious Ship used by the U.S. Marine Corps

LRM – Line-Replaceable Module

LRU- Line-Replaceable Unit

MBT – Main Battle Tank

MTBF – Mean Time Between Failures

MY – Multi-Year, as in Block Purchase Contract

O & S – Operations and Sustainment

OPTEMPO – Operations Tempo

OSA – Open Systems Architecture

OT&E - Operational Testing and Evaluation

PDF – Probability Distribution Function

PIP – Product Improvement Program

PEO – Program Executive Officer

PM - Project Manager

SEV – Smallest Extreme Value

SRU – Shop-Replaceable-Unit

TTP – Tactics, Techniques and Procedures

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