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An Obsolescence Management Framework for System Baseline Evolution—Perspectives Through the System Life Cycle

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ABSTRACT

In military, civil, and commercial systems there exists a need to affordably manage the operational effectiveness of the system of interest through the acquisition and operational stages of its life cycle. Once a system design is baselined and instantiated, then the challenge during development, production, and utilization life cycle stages is to maintain the currency of the physical system baseline to facilitate affordable system support. In essence, the system must adapt to potentially frequent asynchronous obsolescence of its constituent elements, requirements growth (driven by the operational environmental and external constraints such as funding, schedule or risk), and external environment changes. This paper specifically addresses the impact that system element obsolescence has on a system baseline during the various system life cycle phases and provides a framework for affordable system evolution.

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Literature search and consolidation has articulated six integral components that comprise a comprehensive evolution framework through bottoms-up obsolescence management of constituent system elements. Each of the obsolescence management components is tangibly addressed in terms of each system life cycle phase and the available tools and methods. Additionally, each of the obsolescence management framework components is analyzed for life cycle phase applicability and then extended further with the criticality and type of analysis to be done for that life cycle phase. In this way, a project can determine which studies to perform, while in a specific life cycle phase, that maximizes the insight of impending obsolescence for a particular system. Syst Eng

Key words: obsolescence management; framework; technology roadmapping; system costing; obsolescence forecasting; trade study; product selection; product surveillance; health assessment; technology transition; DMSMS

1. INTRODUCTION

Military, civil, and commercial systems are increasingly characterized by capabilities and functions that are highly diverse, ubiquitous, distributed, and continuously available. With an increasing trend towards the use of commercial technology and reusable platforms in the design and development of such systems, there exists a need to affordably manage the operational effectiveness of a system through its development, operational and retirement life cycle phases [Verma, Herald, and Knezevic, 1997; Verma and Plunkett, 2000zaq;1; Defense Acquisition University, 2001]. Operational Effectiveness is depicted in Figure 1 and accounts for the technical effectiveness of the design which includes both the defined performance and its inherent availability, the process efficiency of the accompanying support system that drives the operational availability, and the affordability of the overall system solution across the required operational life cycle. The supportability input of inherent availability shown in Figure 1 is dependent on the availability of the parts. When a part is no longer supportable, it directly impacts obsolescence of the system.

Obsolescence is defined herein to represent when a part (hardware, software, constraint) is no longer able to perform its required function such as; availability for purchase or ability to be repaired affordably. Obsolescence, therefore, includes Diminishing Manufacturing Sources and Material Shortages (DMSMS), technology evolution, and any reason that a part is no longer viable within the system baseline. A system baseline represents a tangible articulation of a specific system solution. The causes that force a system baseline to change are varied and include: obsolescence of the constituent elements that make up the system, requirements growth (which may result from environmental changes or changes in external constraints such as available funding, schedule, or risk), and possible regulatory changes. This paper proposes an obsolescence management framework that allows the systems engineer to determine when system components should be changed as a result of obsolescence and what those changes should be in order to sustain the operational effectiveness of the system in an affordable manner throughout the system lifecycle. The framework addresses the supportability and total ownership cost aspects of Figure 1. This research extends traditional obsolescence management approaches which typically predict obsolescence at the

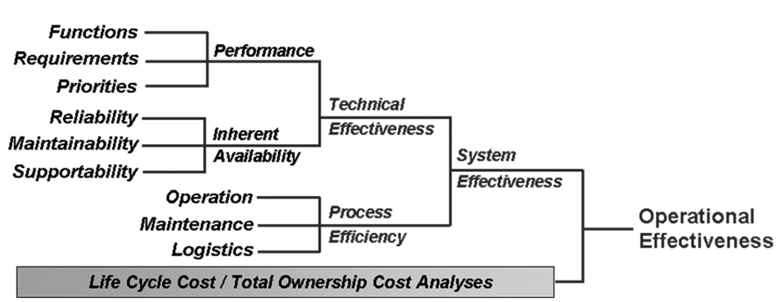

Figure 1. System operational effectiveness.

individual component level or, worse yet, wait until the system baseline is no longer supportable. These fail to address the consolidation of system component analyses that are critical to optimize the system-level operational effectiveness.

The Assistant Secretary of the Navy in the United States published a Memorandum for Distribution [Young, 2005: 2] on system support and evolution planning which requires each new program to: "Manage obsolescence at the piece part level for all active microelectronics. Bill of Material data can be used by program offices and contractors to effectively mitigate obsolescence risk." This memorandum requires addressing part obsolescence in a proactive way and further inspires two discussions: Why was the memorandum necessary and why does it address system obsolescence at the component-level (only a bottoms-up perspective)? First, it encourages proactive management of obsolescence versus a "wait and see" approach that focuses on point-solution support and reaction to an obsolescence event. Reacting to an obsolescence event after it has already occurred, often requires more cost to rectify, and takes on the risk of system downtime which jeopardizes operational schedules. For the second question, from a practical standpoint, the memorandum is needed at some level of the system hierarchy for management of obsolescence, and the current, industry-available, recommended tools directly support component-level obsolescence management. This memorandum provides insight and guidance for obsolescence management of microelectronics and other information technologies which are indeed the faster moving elements of most system solutions and thus require the most critical attention. Therefore, using electronics as a starting point, a system-level analysis should also perform this same level of Diminishing Manufacturing Sources and Material Shortages [DMSMS, 2005] rigor for the other technologies within the physical system solution (i.e., hardware, software, infrastructure and networking, external interfaces, etc.). A strong systems engineering framework must be adaptive for a range of simple to complex systems and for each of the various system hierarchical levels [Shenhar and Bonen, 1997].

Charles Fine [Fine, 1998: 119] effectively indicates the importance of the supply chain design in order to handle the asynchronous barrage of changes to a product while it is in competitive production. A business must decide when to change the product baseline (i.e., re-initiate a life cycle for a new product design) in order to avoid obsolescence of the parts that make up the product and also to maintain competitive advantage and market share. At the University of Maryland Computer Aided Life Cycle Engineering (CALCE) Center, research has progressed to determine an optimized cost effective point for changing the production baseline configuration due to impending or current obsolescence [Solomon, Sandborn, and Pecht, 2000; Singh et al., 2004]. Deciding when to change a system baseline or product during development, production or during the extended operational life cycle phase necessitates attention to a set of obsolescence management aspects. The extension of this system evolution production concept into the system support life cycle phase (or utilization stage per ISO/IEC 15288 Annex B) [ISO/IEC 15288, 2002] is even more critical where the life cycle mismatch between the required operational life of the system and the relatively short life of its constituent elements is more pronounced. This mismatch is often on the order of 10:1, such as for Information Technology systems with long operational life cycles [Seibel, 2005; Herald and Seibel, 2004] of 20–30 years versus the relatively short product life cycles of 2–3 years. For a large integrated system, asynchronous obsolescence events create an ongoing system effectiveness risk.

The need for system evolution management resulting from obsolescence is well established; yet a framework[1] for performing this evolution management comprehensively and affordably requires articulation.{FN1} The framework includes a spectrum of six independent integral components to logically evolve the system baseline through the desired life cycle (system concept, development, production, utilization, support, and retirement) and to effectively manage asynchronous obsolescence events (of the system elements). The evolution is expected and intended to continue through to system retirement.

2. SYSTEM OBSOLESCENCE MANAGEMENT FRAMEWORK OVERVIEW

2.1. Literature Summary

In order to establish the integral components of this Obsolescence Management Framework (OMF), relevant literature was searched and categorized. The research suggests six components that encompass the obsolescence management of subsystems, system elements, and components that constitute a system of

[1]**Framework** \Frame"work'\, n. The development of a good framework takes into account the importance of separating elements of a group into subgroups that are mutually exclusive, unambiguous, and taken together, include all possibilities. In practice, a good framework is simple, easy to remember, and easy to use. Zachman describes a framework as a logical structure intended to provide a comprehensive representation that is independent of the tools and methods used. Sources: *Webster's Revised Unabridged Dictionary* (1913) and [Zachman, 1987].

interest. These components each have significant research support resulting in recommended practices and tools. Variations are also noted in the implementation of each component, such as applicability and criticality in each life cycle phase and the availability of models and tools. These components are the focus of this paper, are briefly defined here, and then are discussed in more detail in subsequent sections.

1. **Technology Roadmapping (TR)** uses technology data and constraints from commercial, civil, research, and military providers to formulate a projected evolution path for existing, system-relevant technologies through the system life cycle. TR represents a relatively near-term (0- to 5-year view, and sometimes up to a 10-year view) technology or product-specific horizon.
2. **System Costing (SC)** leverages the insight from Technology Roadmapping and applies cost to technology (and product) evolution across acquisition, production, and support life cycle phases. Per Figure 1, SC is a key to optimizing technology change decisions and includes acquisition and life cycle cost (LCC) for a total ownership cost (TOC) understanding.
3. **System Obsolescence Life Cycle Forecasting (SF)** uses the technology roadmaps and cost assessments to formulate a predictive forecast of WHAT system elements need to change due to obsolescence and WHEN throughout the system operational life cycle. SF has applicability for each tier of the system hierarchy from the lowest level of procurement. This represents a 20–50+ year life cycle view in support of TOC understanding. For example, the F-35 Lightening II multiservice and multinational piloted fighter aircraft is projecting a 30+ year production and an airframe life cycle of 30 years. Thus the program life cycle easily surpasses a half century. The US Air Force B-52 aircraft is projected to extend its life cycle to 90+ years!
4. **Technology Trade Study Analysis and Product Selection (TS&PS)** uses the forecasted system baseline change needs (due to obsolescence) to identify the available solution trade space for each need, to analyze the tactical technology options, and to select the products to deploy.
5. **Technology / Product Surveillance and Health Assessment (TPS&HA)** addresses the ongoing surveillance of the system configuration, related technologies, and then formulates a system health assessment that is used to recalibrate SF. TPS&HA monitors the ongoing product roadmaps and maturity assessment data to formulate useful decision information for the systems engineer.
6. **Technology Transition (TT)** takes the information from the Technology Roadmaps of known technologies, and combines this with emerging technologies to formulate a maturity metric for the technologies (and their associated products) evolution status and its potential usefulness to the system. TT encompasses three areas of research:
   - Technology Transfer Process Description to evolve a technology from an early stage immature level that is not readily usable in system solutions.
   - Effectiveness Measures to assess the technology maturity.
   - Transfer Methods to migrate the technology from concept to practice such that it becomes a useful contribution to solutions.

2.2. Obsolescence Management Framework Systemigram

In order to place these six obsolescence management components into an OMF, the format of a Boardman Soft Systems Model Systemigram [Boardman and Cole, 1996; Clegg and Boardman, 1996; Sagoo and Boardman, 1998] is used. The interrelationships of these technology obsolescence management components are shown in Figure 2 and describe the activities necessary through a system life cycle due to the obsolescence of its constituent parts. The term system is being used here in the most general sense to encompass from subassemblies through system-of-systems, since all levels may realize obsolescence over time. Figure 2 shows inputs as dark gray circles, OMF components as light ovals, and the systemigram output is the dark oval constituting the system baseline change recommendation.

Technology and cost data are input and transformed into information (understanding relationships) and are then analyzed for system change knowledge (understanding patterns). [Fleming, 2004] The starting points for the OMF data are into the TR, TPS&HA, and TT components with inputs from product providers, academia, laboratories, and research as shown by the dark shaded circles providing inputs to the systemigram in Figure 2. When available, information from TPS&HA is also fed to SF and TS&PS, which then uses these data to formulate change information that will support the systems engineer with trade studies and product selection for TS&PS. While the outputs of each OMF component have specific value, the dark gray oval of Figure 2 represents the integration of this information to provide a system-level baseline change recommendation

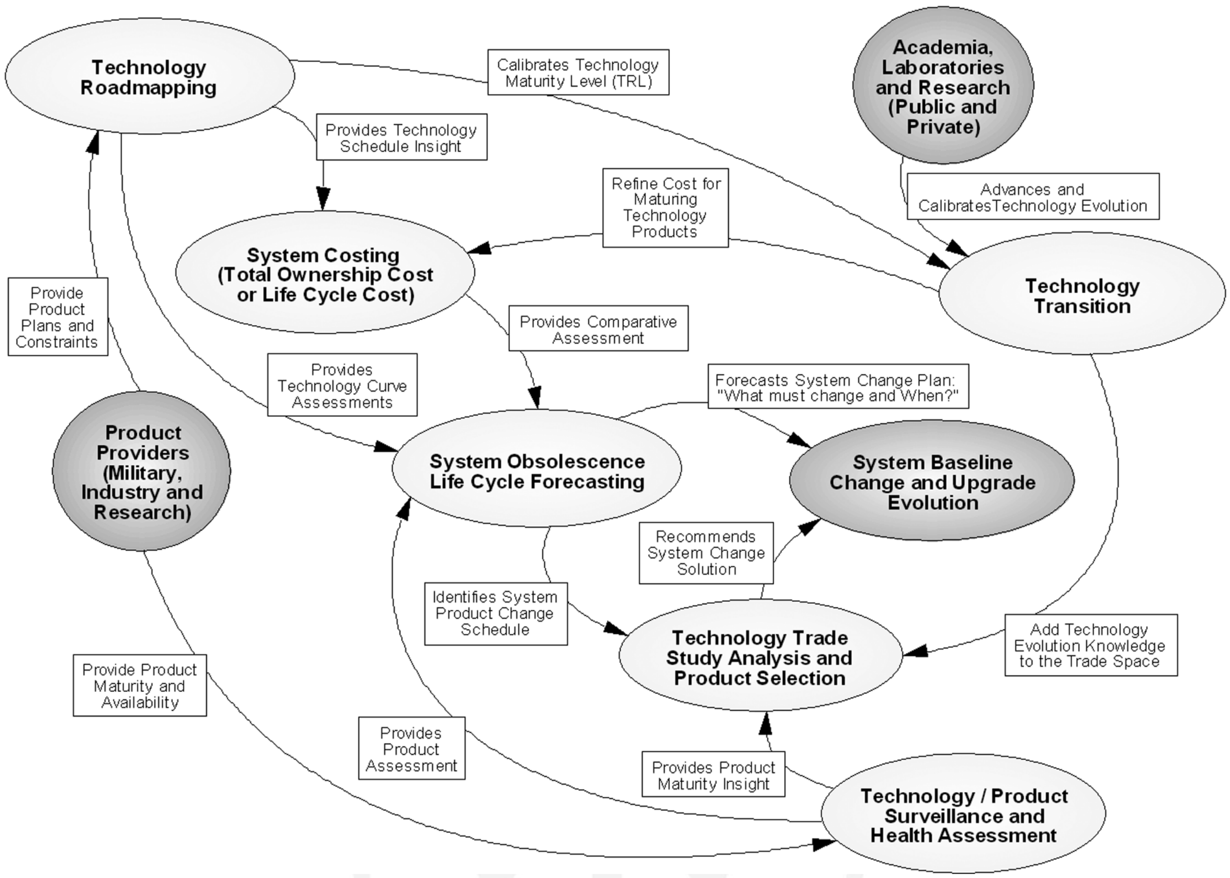

Figure 2. Obsolescence management framework systemigram.

(output of the systemigram). This resultant knowledge permits sustaining a given system in an affordable manner through its operational life cycle.

The systemigram in Figure 2 highlights the *what* to do for OM; however, there are also perspectives for *when* and *how* to do OM through the system life cycle. Section 3 takes the six components of the OMF and discusses each in accordance with its relationship to each life cycle phase (i.e., *when* to do OM) and offers a sampling of current commercial, governmental and academic capabilities tools and methods for implementing each (i.e., *how* to do OM).

2.3. Life Cycle Phases Mapped to OMF Components

As a point of reference, the components of the OMF will be viewed from each life cycle phase as articulated in ISO/IEC 15288 [2002] for determination of applicability and criticality. The life cycle phases described in the ISO/IEC 15288 are:

1. Concept—Perform initial need recognition and explore alternatives with fact-finding that seeds technical and economic feasibility analysis.

2. Development—Transform system requirements into one or more feasible solutions, i.e., system design.

3. Production—Produce, assemble, integrate, test, and certify, as appropriate, each system individually.

4. Utilization—Operate the product or system at the planned operational locations through the balance of the system need. Utilization represents the user perspective.

5. Support—Maintain the system, and provide logistics. Support represents the system viability perspective, and is temporally coincident with the Utilization stage.

6. Retirement—Dispose of the system with considerations relating to environmental effects, contamination, and other hazards.

There are two dimensions to consider when placing the six OMF components against the six life cycle phases. The first dimension is time; i.e., when does a

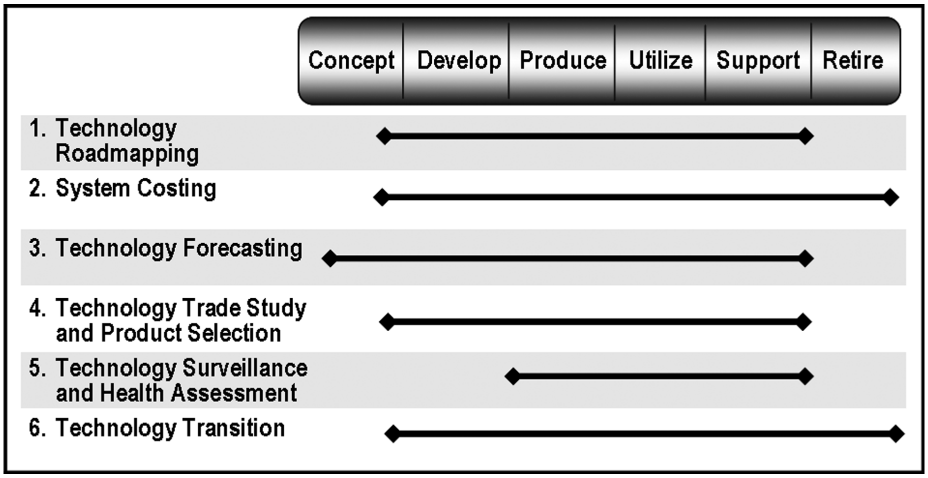

Figure 3. Applicability of the obsolescence management framework components.

particular OMF component have applicability? The second dimension is criticality of the OMF component at each point in the program life cycle. The criticality provides insight into how the OMF component should be applied. Each OMF component is not necessarily applicable in every life cycle phase. Therefore, to notionally appreciate where each of the OMF components has applicability through the life cycle of a particular system, refer to Figure 3. Notice in Figure 3 that there generally exists some degree of applicability beginning late in the Concept phase and continuing through the program life cycle until system retirement.

Section 0 provides discussion of the timing, analysis types, and the degree of criticality of each OMF component through each of the identified applicable life cycle phases.

3. OMF DETAILS AND LIFE CYCLE MAPPING

The OMF provides the integral components of what must be done through the life cycle in order to sustain the viability of the system operational effectiveness. Further scrutiny of the literature reveals that the approaches and tools may vary depending on the particular life cycle phase. This section discusses the criticality of each OMF component in the various life cycle phases, as well as providing a sample of available implementation capabilities and tools.

3.1. Technology Roadmapping (TR)

The purpose for technology roadmapping is stated by Robert Galvin [Galvin, 1998], who is a former Motorola chairman and widely considered as the father of the practice of TR [Schaller, 2004]:

> Roadmaps communicate visions, attract resources from business and government, stimulate investigations, and monitor progress. They become the inventory of possibilities for a particular field, thus stimulating earlier, more targeted investigations.

Roadmapping is usually a subjective exercise that balances possible futures with likely and advantageous futures [Kappel, 2001]. Technology roadmapping details an understanding of both the evolution of specific technologies and the potential solutions for a specific need. Literature describes a variety of roadmap applications such as; science and research, cross-industry, industry, technology, product, product-technology, and project/issue [Kostoff and Schaller, 2001]. From these applications, two perspectives of roadmaps process implementation become evident, technology-push and requirements-pull. These two roadmap perspectives are fundamentally different in that technology-push starts with existing research and products and “looks forward.” The output of a technology-push approach is a Product Technology Roadmap [Garcia and Bray, 1997; Kappel, 2001]. A product roadmap starts with the solution (product) and forecasts it from that point, with the needs for this product yet to be defined.

In contrast, the requirements-pull perspective starts with a desired end product, and searches for solutions, technologies, and products (i.e., looking backward) that potentially meet the desired need. The product of the requirements-pull activity is an Emerging technology roadmap [Garcia and Bray, 1997]. Although the two types of roadmaps are in some ways opposites, both are of value to the system designer depending on what problem is being solved and at which life cycle phase the project currently resides. The primary focus of literature is on hardware roadmapping, and in particular for electronics components. However, the same process approaches can be applied to software, assemblies, and systems. A system-level perspective would require this TR attention for all critical system parts.

Product Technology Roadmap. Product technology roadmaps start with a given solution and are driven by product and process needs. These might include the evolution of an ATM bus or projecting a roadmap for memory density advancement as Gordon Moore, Chairman Emeritus of Intel Corporation, first did [Tuomi, 2002]. These roadmaps are focused on transitioning the existing products through their respective product life cycles to best understand when and how the products might change. These roadmaps strive to accurately predict the detailed evolution of the product both in terms of growth within the product line, and anticipated technological evolution. The roadmaps document a vision that drives more focused company research. This accuracy is a prime concern so the product roadmaps often have a horizon of only five years to sometimes 10 years for slower moving technologies.

Emerging Technology Roadmap. The emerging roadmap is driven by a *need* versus a predefined solution. For example, if there exists a need for energy efficient vehicles, then possible solutions might include lightweight composite materials, Toyota's Hybrid Synergy Drive system [Toyota, 2005], alternative natural gas engine, or low-friction axles. Emerging technology roadmaps identify possibilities and provide a path to identify, evaluate, and select technology alternatives that can be used to satisfy an identified need.

These two TR approaches have varying applicability depending on the particular life cycle phase of the system. Early on in the concept phase, an emerging technology roadmap is useful to identify the opportunities that exist for meeting a particular need. Of interest here is open-minded alternative identification where the criticality of performing this analysis rigorously is low in the beginning but grows to medium as the set of possible solutions emerges. Then the roadmapping method begins to transition from an emerging technology approach to a product approach as the solution space is narrowed to viable candidate technologies. In the development life cycle phase, more detailed understanding of each potentially applicable product is necessary in order to render a proper selection of the baseline technology and eventually the product selection. For this insight the product roadmap is most effective. The criticality of understanding the system baseline technologies is high when production begins, and remains high through the utilization and support phases. The reasons for this criticality involve both maintaining the affordability and consistency of the baseline for the production phase. During utilization, the user is interested in satisfying the functional needs for the employed concept of operations, and it is the emerging roadmaps that allow for injection of innovation (often referred to as technology insertion). During the support phase, the impact of obsolescence is most critical and demands a detailed vision of how each technology in a given system baseline is evolving, so it is the product roadmap that is of greatest interest for sustaining the functional capability. Finally the retirement phase represents a low criticality for TR, accounting for a few considerations such as recycling and re-use. At this point, transition is back to the emerging roadmap for disposal. This summary is consolidated and depicted in the Technology Roadmapping (TR) row of Figure 4.

The impact of ignoring TR is directly proportional to the ability to confidently make appropriate business decisions (schedule, affordability, and functionality) throughout the system life cycle. Without this technology and product-level insight, the decision to change or evolve a system is difficult to render and substantiate.

Available Roadmapping Tools and Methods. Based on foundational work from both Sandia National Laboratories [Garcia and Bray, 1997] and the leadership and coordination of the Center for Technology Roadmapping (CTR) at Purdue University [Duckles and Coyle, 2002] the development and implementation of a tool called Vision Strategist [Alignent, 2008] emerged. This tool allows for the capture and visualization of tactical information regarding specific technologies and begins to fulfill the intent that Robert Galvin articulated. There are many approaches from various industries such as for computer electronics and memory, all with the goal to forecast "what *could* be and what *should* be possible."

3.2. System Cost Analysis (SC)

In performing any system evolution that occurs during any of the life cycle phases, it is almost always the case that a financial analysis is part of the system change decision. The life cycle cost analysis should be included in each system baseline change decision. What is often not so clear is which costs to include in this analysis? There are many ways to look at cost; four categories of cost analysis are considered in this OMF component: Procurement cost, Acquisition cost, Support cost, and Total Ownership Cost (TOC). These costs include the design, purchase, support, and disposal of the hardware and software system elements of a particular system

		Life Cycle Phase					
OMF Tenet	**Purpose**	**Concept**	**Development**	**Production**	**Utilization**	**Support**	**Retirement**
Technology Roadmapping (TR)	Projects product evolution (0-10 years) and solution options for a system need	Emerging TR for opportunities to fulfill the identified system needs	Leverage Emerging TR from Concept phase, and use the Product TR to select baseline solution	Product TR is most effective in evolving the production baseline smoothly	Use the Emerging TR for identifying and injecting innovative alternatives	The Product TR is most critical to understand the impact of obsolescence	The Emerging TR may be of value for recycling and reuse considerations
System Costing (SC)	Provide system-level costing insight for decision analysis	Procurement and Acquisition Costing for technology trade study	Procurement, Acquisition, Support Costing and TOC for engineering trade studies	Procurement and Acquisition Costing are the critical costs to manage baseline affordability	Total Ownership Cost (TOC) is most critical for operational concept trade studies	Primarily Support Costing is most critical, but for re-design, Acquisition and TOC are of value	TOC is of interest for environmental impact considerations
System Obsolescence Life Cycle Forecasting (SF)	Predictive obsolescence forecast for what and when to change the baseline	Leverage the Emerging TR work, and begin SF data gathering on the reduced set of product solutions	Perform SF to support the initial system baseline trade studies (Focus on affordable performance analysis)	SF analysis provides a plan for minimal baseline evolution to maximize production affordability	SF is not applicable for Utilization needs	SF analysis provides a plan for minimal baseline evolution to maximize support affordability	SF is not applicable during the Retirement phase
Technology Trade Study Analysis and Product Selection (TS&PS)	Identifies applicable solution trade space and performs product selection for implementation	From the Emerging TR work, begin TS data gathering on the reduced set of product solutions	Perform TS to understand solution options, and PS to cull the trade space down to an initial baseline	Based on the SF analysis, perform on-going TS&PS as necessary for system producibility	TS&PS is not applicable for Utilization needs	Use the SF plan and perform TS&PS for incremental baseline obsolescence changes	TS&PS is not applicable during the Retirement phase
Technology / Product Surveillance and Health Assessment (TPS&HA)	Gathers technology and product data to monitor system baseline product maturity and longevity	TPS&HA are not applicable in the Concept phase	TPS&HA are not applicable in the Development phase	As the initial system baseline is procured, TPS&HA begins its relevance in support of refining the SF analysis and TS&PS data input	TPS&HA are not applicable in the Utilization phase	TPS&HA are critical for refining the SF plan and providing TS&PS accurate data from actual product-level evolutions	TPS&HA are not applicable in the Retirement phase
Technology Transition (TT)	Methods and metrics for maturing a given technology and trans-itioning technology in a given system	Understanding and projecting the maturity of technology for TT applicability to the system needs	Determine required technology maturity for system needs and level of acceptable scheule risk and system cost	Use TT to determine acceptable schedule risk and system cost for obsolescence changes	TT uses the Emerging TR innovative alternative evolution for potential system value	Provide logical technology and product transition for obsolescence changes	TT may highlight transitions for emerging uses of existing technologies

Figure 4. Obsolescence Management Framework (OMF) mapped across the system life cycle phases.

through its whole life cycle. There are other cost considerations such as social and environmental impact costs that may result from improper disposal (such as ozone depleting gases or ground contaminating leakage); however, these costs are outside the scope of this system-centric OM framework.

Procurement cost. This is the easiest cost to come by for purchased commercial items since it is the cost paid to receive the product. A second consideration is for developed items and in this case the procurement cost is generally the cost to make an additional copy, i.e., catalog price.

Acquisition cost. This represents the cost to instantiate a system baseline. Acquisition includes design and development costs, procurement and material costs, manufacturing labor costs, and, finally, testing costs. This is often described as the cost to design, build, and test a stand-alone system solution. The decision to enter the production phase often hinges on a mutually agreeable acquisition cost.

Support cost. This cost has relevance once a system is instantiated. Support cost includes all elements of cost that are necessary to keep the system operational for the desired operational life cycle. There are varying perspectives on what cost elements should be included in support. There are the traditional logistics cost elements such as spares, repairs, maintenance, and annual software license maintenance that are typical for performing operational support of a system. There are also cost elements for operational resources such as fuel, pilots, and support equipment. The decision on which elements to include is one that must be made and agreed upon for each program. As an example, the US Air Force uses the Office of the Secretary of Defense (OSD) Cost Analysis Improvement Group (CAIG) [OSD, 1992] recommendations for the elements of cost in military aircraft system support.

Total Ownership Cost (TOC). This is the easiest cost to describe and very often the hardest cost to calculate. In short, TOC represents all costs for a system from the time it is conceived until the time it is formally retired and disposed of. The reason that this cost is very hard to put together and estimate is because TOC involves design, development, production, operations, support, and disposal costs. These come from many varied funding sources with varying accounting practices and different cost roll-ups. While consolidating all these cost elements sounds like a trivial summation, the challenging part is finding and compiling the accurate numbers to ultimately sum together [Mandelbaum and Pallas, 2001]. Perspective constitutes an additional complexity when determining the TOC. The perspectives may include a user, a provider, and a paying customer and will likely have result in varying definitions.

When performing a system baseline evolution a comparative understanding of which costs are critical is dependent on the particular life cycle phase, program goals, and desired affordability. The criticality of performing a cost analysis is shown on the System Cost row in Figure 4.

In the early concept phase costing is of low importance, as the system alternatives are defined. However, when it comes time to cull the list of potential candidates down to solidify the initial design baseline, then costing increases quickly to high critical importance. Once these data have been gathered and used to establish the system baseline, then costing tapers off to a moderate criticality through production and support due to the nature of incremental changes being easier to perform. The utilization phase is represented by user analysis of "what if" technology comparisons and the TOC are of greatest criticality. In the support phase, there are elements of support and redesign for obsolescence; thus all cost elements come into play as critical. Interestingly enough, the disposal phase is often viewed as low risk; however, with emerging environmental considerations such as pollution, ozone reduction, nuclear waste, and recycling, the cost analysis returns to a moderate criticality to support the disposal alternatives of the system.

Available System Costing Tools and Methods. There are many costing capabilities from a low complexity spreadsheet-based capability to highly integrated and widely used market tools such as the Price Systems tool suite (H for hardware, S for Software, HL for Logistics, True S, and True COCOMO) [Price Systems, 2008], SEER tool suite (SEER-SEM, SEER-SSM and SEER-AccuScope for Software, SEER-H and SEER-IC for Hardware and Life Cycle, and SEER-DFM for Manufacturability) [Galorath, 2008] and Integrated Desktop Analysis and Planning System Cost Estimation Tool (ICE) used primarily by the US Air Force [Frontier Technologies, 2008]. A new systems engineering cost estimation tool is emerging on the market: The Constructive Systems Engineering Cost Model (COSYSMO) is being offered through the Lean Aerospace Initiative (LAI), which is affiliated with the Massachusetts Institute of Technology. COSYSMO is available through three existing commercial cost estimation suites, PRICE Systems' TruePlanning suite, Galorath's SEER suite, and SoftStar System's SystemStar is a commercial version of the COSYSMO research. "COSYSMO helps large corporations pinpoint systems engineering costs that are factored into planning and executing large system projects. The tool provides an objective approach for government agencies to evaluate proposals." [Valerdi, 2008, 2005] The costing capability that best matches the needs of a particular system should be selected, consistently implemented, and the decisions for evolution should leverage the analyses.

Although not yet available, work at the University of Southern California is focused on a Constructive Cost Model for System-of-Systems Architecting and Integration (COSOSIMO). This extension is striving to climb up the system hierarchy to support cost analysis at the very top of a complex system of systems [Lane, 2006].

3.3. System Obsolescence Life Cycle Forecasting (SF)

As evidenced by the Assistant Secretary of the Navy Memorandum [Young, 2005: 2], the need for planned, affordable system evolution due to the effects of obsolescence is a critical concern in the support of military systems (from small hand-held devices to large-scale network-centric system of systems). Whenever the operational need of the system exceeds the life cycle of the products that make up that system, this life cycle mismatch becomes a concern to the user community of that system. This concern is by and large simple in concept: Provide affordable operational effectiveness [Verma, Herald, and Knezevic, 1997; DAU, 2001]. Once a system has been designed and instantiated in accordance with an operational effectiveness focus, then the challenge during the production, utilization, and support life cycle stages is to maintain the system functionality through affordable evolution [Tiku, 2005].

The obsolescence forecasting component of the OMF addresses the need to evolve a system in order to keep it producible and operationally viable. This includes all hardware and software system elements. The criticality of performing this forecasting in the conceptual phase is moderate in the early concept phase, but, as the technologies and products are narrowed down to a small feasible set, the criticality of performing obsolescence forecasts becomes critical. During the development phase, the decisions rendered for technology and product selection in establishing the system baseline will in large part define the affordability of the system for the remainder of its use. Therefore, visualization, understanding, and forward planning are necessary from this point through the majority of the support phase. As the support phase winds down and then through the retirement phase, obsolescence forecasting is no longer critical at all. The summary of System Obsolescence Forecasting through the system life cycle is shown in Figure 4.

Available Obsolescence Forecasting Tools and Methods. These capabilities are broken down into three subgroups: electronics component obsolescence, assembly obsolescence, and system life cycle management focused capabilities. Each subgroup's capabilities (and associated tools) attacks a different part of the challenge; therefore, a worthy system solution should consider a combination of capabilities in order to fully manage the system.

The first of these subgroups, *electronics component obsolescence*, addresses the lowest level of electronics such as the resistor, capacitor, and ASIC [Huang et al., 2001]. This capability most often uses marketing data analysis as the mechanism for determining current and projected product maturity. [MacNulty, 2002; Pecht, 2003; Meixell and Wu, 2001; Sandborn, Mauro, and Knox, 2007] Some commercial tools also take the next step and strive to provide recommendations for replacement of the particular part that has gone obsolete (ideally this would include a pin-for-pin compatible replacement part that can plug right in without any system impacts). This insight provides the opportunity to proactively rectify the impending obsolescence—often with 30–120 days notice. Commercial tools that fall into this category include: Q-Star [QTEC, 2008], TACTRAC [i2 Technologies, 2008], DNBi Supply Management [D&B, 2008], Parts Plus [Total Parts Plus, 2008] and Advanced Component Obsolescence Management (AVCOM) [MTI, 2008], which is the preferred solution for the US Air Force. These component-level tools are a necessary part of the obsolescence framework in that they each focus on the next obsolescence event forecasting for various segments of changing electronics.

The second subgroup considers *assembly-level obsolescence* capabilities. The focus is on managing an assembly which is made up of hardware components. An assembly will be manufactured, utilized, and sustained. Thus during these life cycle phases, it will be critical to make decisions such as: When is the optimal time to change the system baseline during production, or when is the optimal time to change the system baseline during operations and support?. In order to proactively answer these questions, it is necessary to understand the obsolescence first at the component-level and then aggregate the results to understand the impacts at the assembly level. Assembly-level analysis builds directly on the electronics component-level tools and performs the aggregation and optimization of change recommendations. In fact, some of the industry capabilities such as Mitigation of Obsolescence Cost Analysis (MOCA) from the University of Maryland [CALCE, 2008; Sandborn and Singh, 2006; Sandborn et al., 2003; Singh et al., 2004; Solomon et al., 2000;

Pecht et al., 2002] take the output of tools such as TACTRAC or Q-Star as inputs to the assembly-level aggregation and optimization.

Further extensions of assembly-level analysis are available such as the Obsolescence Management Information System (OMIS) [NUWC, 2008] from the Naval Undersea Warfare Center Division in Keyport, WA. OMIS employs an interesting combination of component-level, system-level and configuration management analyses. Like MOCA, OMIS takes the output of Q-Star and similar tools as the input for the higher assembly analysis. In addition, OMIS provides the user with an interactive graphical interface. For example the hierarchical graphics allow the user to pictorially drill down from an aircraft level, to the avionics system, to a specific avionics subsystem, to the assemblies that make up that avionics subsystem, and finally to the components that make up those assemblies. This visibility of component-level obsolescence is useful for identifying the impact of a particular obsolescence event across a full system implementation. The output is presented as an aggregation of the health status of all the components represented at the hierarchical level of interest.

The third subgroup of commercial obsolescence forecasting capabilities is *system life cycle obsolescence management*. This subgroup is distinguished by two significant extensions over the previous two subgroups. The first is to extend the analysis from the next obsolescence events (or current obsolescence events) prediction to a full life cycle perspective. In this way, financial planning, technical planning, and costing can be more accurately estimated for a life cycle schedule with forecasted obsolescence event points. The second extension is the independence from component-level data, thus allowing any level in the system hierarchy to be analyzed. This independence allows for all system elements to be included in the analysis versus electronics component hardware only. Thus software, firmware, commercial-off-the-shelf (COTS), developed items, as well as electronics component hardware products can now be aggregated into the system analysis for a thorough system life cycle perspective [Sandborn and Plunkett, 2006]. The system life cycle obsolescence forecast requires new data inputs that are not typically available. For example, the component-level tools most often use marketing data of a particular component to determine the maturity of that given component (adopting a typical business "S" curve of product life cycle introduction, growth and saturation phases [Volker, 1988zaq;1]). Therefore, as the market begins to saturate and competing technologies and products emerge, the product of interest matures and the marketing data highlights this. The system life cycle perspective uses knowledge from this typical product life cycle and extrapolates across the desired system-level life cycle for each element in the system of interest.

There is currently a published capability that supports system analysis criteria, the Rapid Response Technology Trade Study, R2T2 [Herald and Hertz, 2004; Herald and Seibel, 2004; Herald, 2003] capability is being jointly evolved with Lockheed Martin and Stevens Institute of Technology. This particular tool strives to support the systems designer and architect with a capability to forecast system obsolescence across the desired life cycle and allow for comparisons to alternative solutions. Once a particular solution is selected, then a life cycle obsolescence plan is documented for the elements (hardware, software, etc.) that will require refreshment and at what points in the life cycle these refreshments should occur. The selected frequency of change can be varied to that which matches program requirements, or it can be optimized for affordability as desired.

3.4. Technology Trade Study Analysis and Product Selection (TS&PS)

This component in our OMF is rich with decision analysis approaches to directly support the comparison and final selection from various solution options. Michael Pecht [2003] offers a summary of approach methodologies particularly for the component-level discussed earlier. Although primarily focused on electronic components (resistors, diodes, and integrated circuits), these same principles and similar assessment criteria [Pecht, Syrus, and Humphrey, 2001] have applicability up through the system hierarchy and can be adapted for hardware and software, whether they are COTS or developmental items. The point of this component is to support a methodical approach to whittling down the list of reasonable and competitive products for a particular system application. Criteria for product selection include [Verma et al., 1996; Verma and Johannesen, 1999]:

- Performance and Functionality
- Cost (Acquisition, Support, Licensing)
- Training
- Reliability, Maintainability, and Availability
- Procurement and Vendor (product availability, stability, experience, market share)
- Configuration Management
- Technical Documentation and Data Rights
- Assembly and Installation
- Open Architecture and Standards.

This element of our OMF has critical applicability when the initial product selections are being determined for the detailed design phase. This criticality remains high while the system configuration is still evolving in response to system element changes until the point during production where the final production configuration is determined. At this point during the utilization of the equipment, there is very low criticality for this analysis since the product meets the functional requirements. However, when the system changes due to emergent requirements or obsolescence during the utilization phase, the criticality again goes up in direct support of system refreshment and insertions. Although the criticality in the retirement phase is low, this assessment could be re-leveraged to evaluate the possible advantage for recycling or reuse of the system equipments. Figure 4 shows the Technology Trade Study and Product Selection (TS&PS) life cycle phase applicability row in the framework.

Available Technology Trade Study and Product Selection Tools and Methods. The commercial product selection criteria above highlight the strengths and weaknesses of each of the alternatives so that the aggregation can be assessed and compared. Typical commercial tools for performing these type of analyses include spreadsheet models such as Kepner-Tregoe Matrix Decision Making Method [Kepner-Tregoe, 2008] and the COTS/NDI Assessment and Selection Tool (CAST) [Verma et al., 1996] (NDI is a Non-Developmental Item). The CAST model uses the Analytic Hierarchy Process (AHP) [Saaty, 1980], which is a multivariable decision analysis aid that provides two benefits over the spreadsheet methodology. The first benefit is the use of pairwise matrices. In this way the subjectivity of the criteria weightings is minimized to one-on-one comparisons versus many-to-many. This eases the time and difficulty of model development. The second benefit, once the input criteria model is complete, is the calculation of an Inconsistency Ratio, which represents the ratio of the percent of inconsistency divided by the model consistency. Using the inconsistency ratio, a user can have confidence that the input model has been consistently described, and consequently the outputs are equivalently reliable. Since the goal of a product selection is to analyze multiple attributes simultaneously, a method that accounts for all of the various program criteria in a methodical way is sufficient.

3.5. Technology and Product Surveillance and Health Assessment (TPS&HA)

This component of the framework takes place, as shown in Figure 2, after a system configuration baseline has been established, typically at the end of the development phase. As soon as the configuration is set, the need for technology surveillance to assess the health and maturity of the system products (including hardware and software) is necessary. Paul Schutte from NASA Langley Research Center asserts that "... technology is used primarily for monitoring and implementation and humans are used primarily for generating alternative actions and selecting among those alternatives" [Schutte, 1999: 116]. TPS&HA leverages a mix of tools for monitoring and providing information to the systems engineer. This information can be formulated at each level of a given system's hierarchy, keeping in mind that it is necessary to fully understand the current status of each of the elements that make up that system level and aggregate information of the impending obsolescence.

This information is used to support the SF and TS&PS OMF component analyses as shown in Figure 2. The input data is typically obtained from product providers in the form of: technology roadmaps (product type), technology forecasts for those items where a roadmap is not available (this includes all three levels of component, assembly, and system forecasts), and cost analyses. In this way, an aggregation of the lowest-level information can be formulated to understand next higher-level impacts. Specific implementation plans will be chosen by the systems engineer, depending on the program constraints.

This analysis is not intended to cover an industry sampling of available technologies and products, but rather this analysis is performed for a specific system instantiation and its associated bill of materials. This analysis is intended to cover all technologies and products (hardware, software, etc.) that are in the system solution. The criticality of this component is low until the system baseline is established and even until the first obsolescence begins in production. After this point and up until system retirement surveillance is very critical to the continued operational effectiveness of the system of interest. Figure 4 summarizes the TPS&HA row in the OMF.

Available Technology and Product Surveillance and Health Assessment Tools and Methods. The Technology Roadmapping tools discussed in Section 3.1, the System Costing tools in Section 3.2, and the System Obsolescence Forecasting tools discussed in Section 3.3 provide the input set for this ongoing technology and product surveillance. To assess the health status of the system, there are capabilities such as the US Navy's Obsolescence Management Information System (OMIS) [NUWC, 2008] and the COTS Database from Lockheed Martin Maritime Systems & Sensors [Herald and Genaw, 2005]. A screen capture of a portion of a system health status assessment is shown in Figure 5 and represents a tangible basis for a systems engineer to determine an ideal point for system evolu-

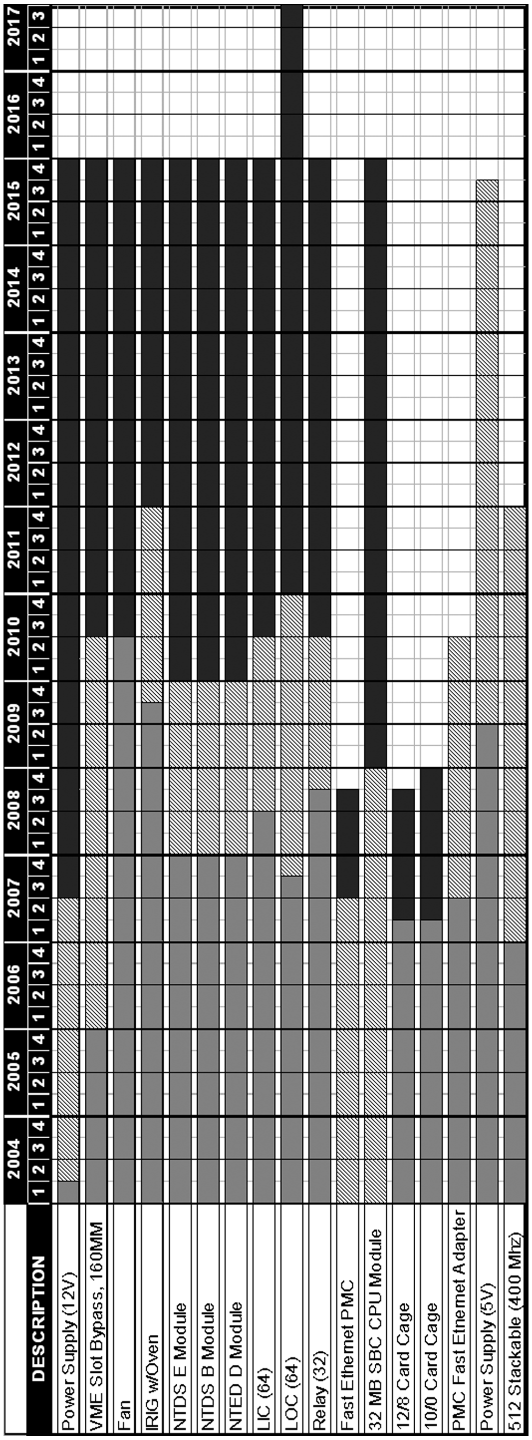

Figure 5. Partial system health assessment screen capture from the COTS database.

tion or for alternative product solutions. In Figure 5, the light gray bars represent the expected duration of product manufacture and availability, the slashed bars represent the period of announced or extended support from the original equipment manufacturer, and, finally, the dark gray bars represent the anticipated period of product availability (and possibly support) from possible aftermarket and third-party sources. Notice that starting in the 5th year of the program (2008), three products will require a proactive solution. This solution may come in the form of a replacement (through redesign or compatible replacement), or through product emulation (also a development solution that replaces the existing capability with a new technology such as using gate array technology to replace an aging processor), or, finally, with the procurement of a stockpile of spare parts that are expected to extend the actual end-of-support date to some future point. Each of these options entails additional costs, schedule, skills and resources, retesting, and recertifications. Trading-off when the cost of redesign becomes less than the cost of product stockpiles is critical to understanding for system evolution decisions.

3.6. Technology Transition (TT)

The origin of technology comes from Greek roots with "Techne," meaning skill of hand or technique, and "Logos," meaning knowledge or science. From these roots, the term technology transition (or technology transfer) has taken on a variety of definitions. From examination of this diverse academic literature, three distinct groupings of study have emerged [Lipp, 2002]:

- Descriptions of the technology transition process
- Measures of the effectiveness of technology transition
- Methods to more effectively transition technology.

These groupings cover the essence of the challenges faced by practitioners regarding the process to advance a specific technology along its maturity scale from original concept to application and eventually into historical archives. This OMF component monitors the advancement of technologies as possible solutions to system obsolescence. In order to further define the framework, the three categories will be expanded.

Descriptions of the technology transition process. There are two primary perspectives of transition for technologies. The first perspective regards the advancement of a technology from one maturity stage to the next within its own purview. The second regards the movement of a particular technology from one environ-

TRL 9 – Actual system “flight proven” through successful mission operations
TRL 8 – Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 7 – System prototype demonstration in a space environment
TRL 6 – System/subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 5 – Component and/or breadboard validation in relevant environment
TRL 4 – Component and/or breadboard validation in laboratory environment
TRL 3 – Analytical and experimental critical function and/or characteristic proof-of-concept
TRL 2 – Technology concept and/or application formulated
TRL 1 – Basic principles observed and reported

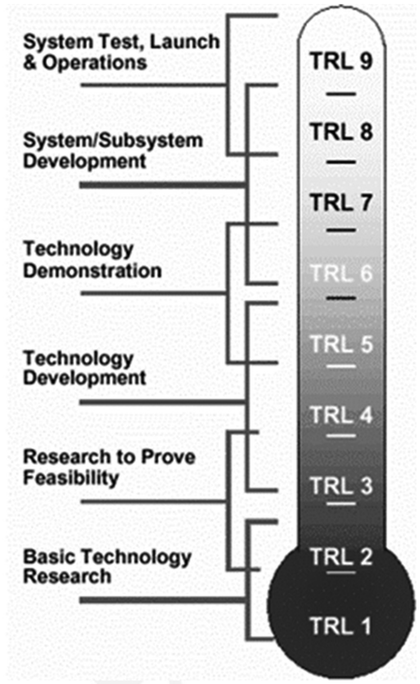

Figure 6. Technology readiness level process evolution descriptions.

ment to another such as from a laboratory/testing environment to an operational environment as a part of a deployed system. These perspectives have been combined into a transition process structure called Technology Readiness Levels (TRL). TRL provides a framework to describe the process for transitioning a technology from Basic Technology Research to Technology Development to Technology Demonstration and, finally, to System Test, Launch, and Operations. The TRL system was formally adopted by the U.S. National Aeronautics and Space Administration (NASA) for research project tracking and management in 1991 [Wikipedia, 2008]. Since that time, several prominent organizations such as the Defense Advanced Research Projects Agency (DARPA) have leveraged TRL as a process for monitoring the formal progress and maturity of a particular technology through its life cycle. A description of the TRL process for NASA includes nine different levels as delineated below, and Figure 6 highlights the process evolution across the TRLs [Mankins, 1995].

The TRL framework provides the process trail that sets the expectations for what must be accomplished to move a particular technology forward in maturity. As can be seen from the TRL descriptions above, the linkage to application-specific environments is certainly a consideration when selecting technologies. Therefore, a specific technology may reach a TRL 6 and be ready for prototyping in a space application; however, that same technology may only be at a TRL 4 for an automotive industry or undersea application. This technology readiness awareness creates a context around which the transition challenge can be methodically addressed.

Measures of the effectiveness of technology transition. The TRL structure provides a process for transition and has enumerated a scale for measuring the current status of a given technology. The effectiveness of transitioning from one level to the next is now more evident. This insight permits the technology-specific metrics for effectiveness measure to be determined and subsequently tracked as the technology advances on the maturity scale. Other metrics consider the timing, the risk, and the quality of the transition in order to better plan for transition into systems.

Methods to more effectively transition technology. The Office of Naval Research (ONR) describes the transition of technology using two perspectives: the movement of an actual technology into a new application and the transfer of knowledge relating to the actual technology from previous applications. As an example, ONR addresses these perspectives by breaking out technology into thirty-one different primary categories with each one being further refined to approximately 2–20 different subcategories with then 3–5 different subject matter experts that represent the various capabilities.

This network of technical expertise is a treasure of resources being offered specifically to innovatively move technology information into sectors where it has immediate application and for application in commercial and governmental sectors where it was not originally envisioned. This part of technology information transition is exciting because of the unknown potential unleashed by the network of domain expertise. The challenge for a project (new or existing) is to proactively pursue and leverage these resources to drive innovation into new designs and system evolutions.

Other organizations have also embraced the significance of moving technology from the laboratory environment into real-world applications with DARPA being a superior example. In a formal document published in the late 1990s [DARPA, 1997], DARPA describes military platform successes of stealth technology transition, unmanned aerial vehicle (UAV) flight, the common affordable lightweight fighter demonstration that lead to the Joint Strike Fighter common platform with variants, and many more examples of ground-breaking technology work that has made the jump from lab concepts to innovative applications. There are also many non-DoD applications that have arisen from DARPA-sponsored technology transition, the Internet (from the ARPA Network and Milnet) being just one. So how does DARPA move technology from the conceptual phase to availability for military implementations? Investments are made to incrementally evolve technology in a methodical way. Those technologies that show incremental progress and promise against the TRL scale are prioritized for the available funding of the next investment year. If successful, this initiates development leading to a demonstration. Once this demonstration has proven the initial concepts and possibly exposed the potential for adjacent sector use, the technology is reviewed for possible applicability and deployment. This transition method provides multiple checkpoints along the way to reassess the value, push it in a certain direction, or change the anticipated environment, as well as determine if the technology should be halted in favor of more promising options.

The performance of technology transition assessment and planning is most critical in the beginning of the program life cycle where the newest technologies are being traded against established technologies for hardware and software products. It is necessary to assess the status of technologies and product alternatives for the TR OMF component. As the program moves into the development life cycle phase, technology transition remains equally as critical since the design can be updated at any point within development. During the production phase (after the system baseline has solidified) and on through the utilization phase, technology transition is based more on opportunity rather than necessity. When an opportunity presents itself it should be studied by the TS&PS component. For the support phase, there is not an urgency for technology transition of the system configuration since functionality is in place and operational; however, technology transition could be leveraged for potential system improvements. In the utilization phase data transfer from the design team to the operational team is most critical. The retirement phase accounts for the opportunity to leverage emerging uses for existing technologies (such as for recycling and reuse applications). Figure 4 summarizes the applicability of technology transition as the final row in the OMF.

4. CONCLUSIONS AND FURTHER RESEARCH

4.1. Conclusions

In order to ensure the continued operational effectiveness of a system through the design, production, utilization, and support life cycle phases, an Obsolescence Management Framework (OMF) is proposed for a system design and evolution. The OMF articulates the six integral components necessary to protect a system from operationally ineffective evolution due to obsolescence of the elements making up that system. From a practical perspective, the OMF supports the system stakeholders with initial baseline definition and with proactive obsolesence planning. The systems engineer, who is responsible for the design of the system architecture, begins forecasting the impact of decisions rendered in the early project stages. The systems designer, who is responsible for selecting the baseline solution and then the smooth evolution of that baseline, must understand what technology and products are available, must perform trade studies to balance technical, cost, and schedule constraints for a best value recommendation, and must integrate evolving technologies as appropriate. The answers for When to change the system and What must change at those points are developed with the OMF as a guide.

The six OMF components are then explored in two dimensions. The first dimension is the applicability of each component in each typical life cycle phase. The second dimension is the criticality in each applicable life cycle phase. From this contextual setting a system engineer can best apply the available industrial capabilities at the most beneficial points in the life cycle. Although obsolesence is obvious and critical in the utilization and support phases of a program life, an interesting observation of the literature shows the critical applicability of these OMF components in even the earliest conceptual and design phases. Another observation is the varying usage of component capabilities through time; for example, technology roadmapping applicability moves from product roadmapping needs to emerging roadmapping needs and back again as the system evolves. The OMF focuses these analyses for best value.

4.2. Further Research

The management of system evolution entails affordably changing the baseline while maintaining or improving mission operational effectiveness. The complexity of a system increases as the focus moves from the lowest system elements to the higher hierarchical levels, leading possibly to a networked system of systems where the complexity of maintaining technical viability multiplies exponentially [Cares, Christian, and Manke, 2002]. Further research opportunities exist to extend the OMF and address the complexity through the system hierarchy.

- The focus of this OMF is on the evolution of systems solely due to the obsolescence of the constituent elements that make up that system. It addresses the system as a constant functional baseline over time while allowing just the physical baseline to evolve. There is often a desire to enhance the system functionality through the expected system utilization phase to handle such needs as emergent external system influences, desired capability growth requirements, and technology insertion for the sake of a particular system value (i.e., not due to obsolescence issues, but possibly for such benefits as reliability improvements). Just like obsolescence considerations, these real-world functional considerations are also directly applicable to the physical system evolution.
- An aspect of the Technology Trade Study Analysis and Product Selection OMF component considers the change in technical performance when a system baseline evolution occurs. This is not explicitly discussed in this paper and yet represents an interesting area for further research. How much additional system functionality is realized when the technology and product baseline changes? The system impact may be negative or more likely the impact may provide greater capabilities than its technology and product predecessor did. The further research might address trade study quantification, leverage, forecasting, and planning.
- Consider using the OMF to create a "professional survey" that gets distributed to a sample of Systems Engineers for Review, Modification, and Comment. This survey data can then be used to corroborate and provide credibility for this literature analysis.

5. ACRONYMS

AHP Analytic Hierarchy Process
ARPA Advanced Research Projects Agency (started in 1958; predecessor to DARPA)
ATM Asynchronous Transfer Mode
CAIG Cost Analysis Improvement Group (sponsored by the OSD)
CALCE Computer-Aided Life Cycle Engineering Center (University of Maryland)
CAST COTS/NDI Assessment and Selection Tool (Lockheed Martin Corporation)
COCOMO Constructive Cost Model (University of Southern California)
COSYSMO Constructive Systems Engineering Cost Model (Massachusetts Institute of Technology)
COSOSIMO Constructive Cost Model for System-of-Systems Architecting and Integration (University of Southern California)
COTS Commercial Off The Shelf
CTR Center for Technology Roadmapping (Purdue University)
DARPA Defense Advanced Research Projects Agency
DMSMS Diminishing Manufacturing Sources and Material Shortages
ISO/IEC International Organization for Standardization/International Electrotechnical Commission
MOCA Mitigation of Obsolescence Cost Analysis
NASA National Aeronautics and Space Administration (United States)
NDI Non-Developmental Item
NUWC Naval Undersea Warfare Center
OM Obsolescence Management
OMF Obsolescence Management Framework
OMIS Obsolescence Management Information System (US Navy)
ONR Office of Naval Research
OSD Office of the Secretary of Defense
R2T2 Rapid Response and Technology Trade Study (Lockheed Martin)
SC System Costing
SF System Obsolescence Life Cycle Forecasting
TOC Total Ownership Cost

TPS&HA Technology/Product Surveillance and Health Assessment
TR Technology Roadmapping
TRL Technology Readiness Level
TS&PS Technology Trade Study Analysis and Product Selection
TT Technology Transition
UAV Unmanned Aerial Vehicle

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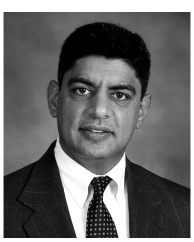

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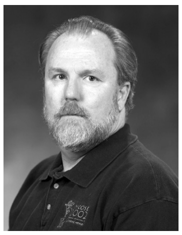

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