# COTS Parts Obsolescence Management of Sustainment Dominated Military Systems

**Barış Egemen ÖZKAN**
Marmara University
Author
TURKEY

begemenozkan@hotmail.com

**Serol BULKAN**
Marmara University
Author
TURKEY

sbulkan@marmara.edu.tr

## *ABSTRACT*

*Recent and complex challenges, continuous military budget cuts and the breakneck speed of technology have forced nations to align their military system procurement strategies to embrace more Commercial Off-The-Shelf (COTS) products. Nearly every nation places as much emphasis as possible on the use of COTS products in sustainment-dominated systems. While there are numerous advantages to using COTS products, there are also a number of disadvantages. Some of those disadvantages include product volatility, obsolescence and being outdated. Therefore, the sustainability of systems with product life cycles of 25+ years is of critical concern especially when we consider availability and accessibility requirements. Obsolescence is considered to be a major problem for sustainment dominated systems and it needs to be managed. If not properly addressed, obsolescence creates a huge financial burden on maintenance agencies. Therefore there have been numerous studies and acts on obsolescence by government organizations, industry and academia. In this study, we conducted a comprehensive literature review for obsolescence management in sustainment-dominated systems using a thematic and chronological review model.*

*Keywords: Obsolescence Mitigation, Obsolescence Management, COTS*

## 1.0 INTRODUCTION

We had experienced tremendous changes in our life in the 20th century. Ever since the invention of semiconductors, the world has been exposed to head-spinning change driven primarily by rapid technological advancement. This century is undeniably incomparable to any other century when considering the pace of change in our lives.

During the Cold War period, the technological advances were primarily driven by military needs and systems. However ever since the collapse of the Berlin Wall, the consumer electronics market segment increased its market share so much that eventually it became the dominant market, especially in the electronics segment. As the technology advanced, the higher market share of electronics and integrated circuits moved from military products to small-scale consumer products. (Romero Rojo, Roy, and Shehab 2009)

Breathtakingly fast technological advances created new consumer markets for which the needs were constantly changed by either producers or consumers; thus, the life cycle of consumer products became very short. This phenomenon created a new type of product, called Commercial Off The Shelf (COTS).

COTS stands for software and hardware products or services available in the market for public use that are free of charge or that have a cost associated with them. These products are available for use in any system design; additionally, they are attractive with their low cost and availability within their life cycle time.

This has lead to inevitable changes in how states procure military systems. Following Perry Notice, eventually almost all nations, regardless of the proportion of the military budget, have placed as much emphasis as possible on the use of COTS products. Many state acquisition agencies and departments now strongly advise a policy that focuses on a gradual withdrawal from military specifications (Mil-Specs) and the use of COTS systems if applicable. (Great Britain 2005) (Turkey 2012)(USA 2000)

This fact along with the rapid changing market trends have forced commercial vendors to shift their focus to consumer product lines and to adopt themselves to the fast changing COTS paradigm. As a result, some of the vendors have already left the military market as in the case of Intel Corp (Bartels et al. 2012).

While there are numerous advantages to using COTS products, there are also a number of disadvantages as well. Some of those disadvantages include product volatility, obsolescence, security (Koch and Rodosek 2012) (Rajagopal, Erkoyuncu, and Roy 2015). Even though reduced maintenance costs are considered one of the advantages of using COTS products, they have turned into a barrier for maintenance agencies when we consider the disadvantages mentioned above. The drawback of using COTS systems in systems with longer life cycle periods is their short life cycle periods which are typically 2-5 years. Sandborn calls this phenomenon “Dark Side of the Moore’s Law” (P. Sandborn 2008b).

However not every system is ready to adopt itself to the new phenomenon. Industries including military, aerospace, nuclear energy plants and railways still have life cycles of 25+ years. Due to high investment, testing and certification costs as well as the stagnant nature of the requirements, these systems seem to remain within their long life cycle periods. These systems are considered to be “sustainment dominated systems” (P Singh et al. 2002).

Maintenance and sustainability costs of sustainment-dominated systems are considerably higher than those of any other system and it is harder to maintain those systems for various reasons such as the complexity and the nature of the system which requires a huge amount of requalification as well as the certification requirement for a design change due to obsolescence. Sometimes, certain COTS products go obsolete even before production starts. Therefore, obsolescence is a major problem for systems with a long life cycle and this problem has to be addressed by an Obsolescence Management Plan (OMP) as early as possible (Romero Rojo, Roy, and Shehab 2009). The lack of management and poor planning for obsolescence cause companies and governments to spend progressively more to deal with aging systems.

According to Qinetic, a North American company, approximately 3% of the entire world’s electronic parts pool is becoming obsolete and this figure is not improving as time goes on (P. Sandborn 2007). If this problem is not addressed properly, the economic consequences could be financially overwhelming for the organization. For example, a US Navy shipboard sonar system development project experienced the obsolescence of 70% of the parts listed in BOM even before the system had completely developed (Pameet; Singh and Sandborn 2006). Also, the US Air Force spent $81 million USD to change and redesign the electronic parts for F-22 program. The redesign of a system used in F-16 fighters radar systems cost $500 million USD for the US Air Force (McDermott 1999). The Electronic Industries Alliance (EIA) Manufacturing Operations and Technology

Committee reported that cost for the redesign of an obsolete electronic part is between $26,000 and $2 million USD. In 1997, the US DoD (Department of Defense) spent $264.000 USD for Life-of-Type Buy for an obsolete part. The US DoD is reported to have spent $10 billion USD to manage and to mitigate obsolescence problems (Feldman and Sandborn 2007).

This study is the first part of "Obsolescence Management for Military Systems" research carried out at Marmara University/İstanbul. The ultimate goal of this research is to develop an Obsolescence Management model for military systems, which considers the whole life cycle costs of the systems.

In this study, we conducted on a comprehensive literature review for obsolescence management in sustainment dominated systems. In the second section we outlined the obsolescence management strategies. In the third section we gave a comprehensive review of studies and legislative actions including doctrines, guidebooks, obsolescence strategies, mitigation techniques and models. In the forth section we defined the methods and procedures we used in the review. The research concludes with the results and conclusions.

## 2.0 OBSOLESCENCE MANAGEMENT STRATEGIES

As each study draws attention to obsolescence, the proposed methods, methodologies and models for obsolescence are ultimately formed around strategies forming a three-tiered solution (P. Sandborn 2008a):

- Reactive management strategy methods
- Pro-active management strategy methods
- Strategic management methods

Reactive strategies are the least cost effective ones even though in some rare cases this may be the optimal solution to follow until a proactive or strategic solution milestone such as a Design Refresh date is devised. In a reactive strategy, no action is taken until obsolescence occurs. Once obsolescence occurs, different types of reactive mitigation techniques may be applied. Some of those techniques are Life-Time Buy (LTB), Bridge Buy, Reverse Engineering, Redesign, and Emulation. Each one of these techniques comes with an associated cost. An optimal solution may include one or more of these techniques. Several considerations are taken into account while selecting the techniques such as the number of obsolete parts in the system, expected lifetime of the system, future demand, testing and re-certification costs.

Proactive strategies favor the monitoring of parts before they actually become obsolete and aim to prevent obsolescence driven risks. As monitoring all the materials in the system may not be feasible, only peculiarly selected parts are closely monitored and managed by a group of experts on obsolescence. Clustering parts based on the obsolescence risk and adjusting the level of management based on clusters is another to apply the strategy. Proactive management is performed during design, production and after sale phases. Each selected part is analyzed against obsolescence risk and graded. The Material Risk Index and Progress Indicator are two of the metrics used for such purposes. This is not a one-time process but it is performed continuously until a decision is made not to do so.

Strategic obsolescence management is a holistic approach which includes both reactive and proactive strategies as well as strategic level managerial actions. It starts even before the product design phase. Systems must be designed for obsolescence. One of the most common ways of achieving this is to design loosely coupled components with standard interfaces so obsolete parts can easily be replaced with others. Strategic level management requires planning for obsolescence. This plan must be continuously reviewed and is subject to change if necessary. All systems and system parts need to be planned, designed, produced and maintained with the mindset that product life cycle costs are always considered. It requires forecasts for both the demand and obsolescence of parts while estimating the best point in the product life cycle to refresh the design; if necessary it combines the most feasible reactive methods till the design refresh date. It requires institutional level obsolescence awareness and the development of an organizational culture for obsolescence. Supply change management is another major part of strategic level management in order to prevent obsolescence. Long-term agreements with suppliers are considered to be one of the most effective ways to prevent obsolescence.

## 3.0 OBSOLESCENCE STUDIES

Even though the studies on obsolescence in military systems date back to the 1960s, the major focus of the years between 1960 and 1990 was the problems with inventory. The aim was to find the optimal point to maximize the effectiveness of weapons with variables that represented quantity and quality of weapon systems (Weiss 1961) as well as to estimate/find the future needs for spare parts. Even though obsolescence was still assumed to be a part of that equation, it wasn't the major focus of those research.

In 1994, the US Secretary of Defense formally initiated a new way of doing business and proposed a challenge to the DoD: *"...change the way of procurement basically and fundamentally. We have to buy more commercial products, we have to make greater use of commercial buying practices, and we have to use industrial specifications in place of military specifications*." This is known as the Perry Notice and it was a turning point for US defense program managers as it saw greater use of COTS/NDI equipment and left MIL-SPECS alone, as much as was possible, so as not to jeopardize the military objectives (USA 2000).

The DoD's motivation to increase the usage of COTS equipment in military systems was to reduce weapon system acquisition and support costs as well as take advantage of the fast pace of commercial technology change while also minimizing the costs(Haines 2001). However, this motivation created a new phenomenon that is now known as the obsolescence problem.

For almost 30 years there have been numerous studies on obsolescence. Those studies can be clustered into three main parts. The first cluster includes the activities conducted by governmental organizations. The second cluster includes the studies conducted by the defense industry and government supported research labs as well as services. The last cluster includes studies conducted by academia.

### 3.1 Organizational Acts on Obsolescence

Following the Perry Notice, The US Department of Defense (DoD) issued a Military Handbook for Continuous Acquisition and Life-Cycle Support (CALS) to enable more effective generation, exchange, management, and use of digital data supporting defense systems (Department of Defence 1994). The primary goal of the CALS strategy was to migrate from manual, paper-intensive defense system operations to integrated, highly automated acquisition and support processes. The fingerprints of the continuous acquisition of life cycle support can be considered the early signs of Performance Based Logistics (PBL).

As more COTS parts are being used in military systems, US DoD named the obsolescence problem "Diminishing Manufacturing Sources and Material Shortages (DMSMS)" and a DMSMS Working group was established by the US Deputy Under Secretary of Defense for Logistics (DUSD (L)). The aim of the working group is to foster the development of DMSMS management techniques, tools, and policies to increase readiness, to sustain wartime operations, and to reduce life-cycle costs of DoD weapon systems.

Towards the end of 20th century, as the US DoD defined DMSMS as a problem that needed to be managed, the major focal points were the assessment of technology obsolescence and the impacts of obsolescence on business and product life cycle (Hitt and Schmidt 1998) as well as the approaches to reduce the impact of such technical obsolescence (Pertowski and Denham 1998).

Following on the studies that highlighted the effect of obsolescence and how to mitigate it, the Electronic Industries Alliance (EIA) established a "Data Warehouse" that would store data on component availability, projected life expectancy, usage in defense systems and sources of supply. The whole idea was based on the idea of collecting data from the vendors of the electronic products and make it available for further analysis by both analysts and project/program managers during the acquisition, design and maintenance periods. The motivation for such a data warehouse developed out of not only defense needs but also commercial needs. This data warehouse and other similar databases established a framework with its extensive data for future academic studies.

At the end of the 20th century, the Deputy Under Secretary of Defense called more attention to obsolescence and so in 1999 the Logistics branch requested that the DMEA develop cost factors for all DoD programs to uniformly report the cost avoidance associated with their DMSMS programs. The DMEA awarded this study to ARINC to develop cost factors in obsolescence management. The study reveals the cost factors of reactive mitigation techniques and claims that the cost avoidance for a sample system is up to $2.5 million USD.

At the beginning of the 21st century, following reports, studies and research on obsolescence, the US Navy issued a policy for COTS equipment(USA 2000). It was prepared by the COTS Steering Board as a response to the feedback from the NAVSEA COTS Workshop held in 1998. The purpose was to establish a policy for expanding the use of COTS products while also managing their risks in military systems. The scope of the policy was naval systems procured by NAVSEA and its affiliated programs. The policy did not say how to handle obsolescence, but instead provided guidance as well as defined what must be addressed. Certain issues in the procurement policy that needed addressing were pointed out some of which included COTS equipment and its design.

As obsolescence is recognized as a serious problem in multiple disciplines, the US DoD ordered the DMEA to produce a handbook for program managers. The DMEA awarded the contract to ARINC to produce a guidebook for Program Managers. In 2001, ARINC delivered the Program Managers Handbook, Common Practices to Mitigate the Risk of Obsolescence (Tomczykowski, Fritz, and Scalia 2001). It is a collection of guidelines for program managers of military systems to mitigate the risks of obsolescence so that the impacts and the costs of obsolescence can be minimized.

In addition to this policy, the US DoD released another guidebook for increased reliability and a reduced logistics footprint for program managers (Department of Defense 2003). The updates to the US DoD doctrines 5000.01 and 5000.02 changed military systems acquisition methods; the model has changed the acquisition model to the spiral model in order to reduce acquisition and deployment duration. Program Managers (PM) are not only responsible for the timely acquisition of systems, but they are also responsible for the whole life cycle of the system for sustainability. Therefore, PMs have to design for the total life cycle management costs of any weapon system.

In 2004, the US DoD released two guidebooks for program managers. The first one is the updated Performance Based Logistics guidebook for Program Managers. It gives guidance to program managers with its updated content, enriched by experiences from the Afghanistan and Iraq wars; it also provides methodologies for performance based logistics and key issues in implementation processes (Department of Defense 2004a). The guidebook is all about total life cycle cost management and proposes that Program Managers use spiral development and open systems to mitigate obsolescence. The second US DoD guidebook is the Product Support Boundaries (Department of Defense 2004b).

Following the guidebooks, the US Department of the Navy (Department of Navy 2005) and the US Coast Guard (United States Coast Guard 2012) released their own DMSMS Management Plan in 2005 and 2012 respectively to attract attention and to provide guidance to program managers about obsolescence management.

Defense Standardization Program Office (DSPO) published DMSMS guidebook: A Guidebook of Best Practices and Tools for Implementing a DMSMS Management Program, SD-22 and the latest edition is released in 2016 (Defense Standardization Program Office 2016). It includes proactive practices for program managers to mitigate obsolescence by using various methodologies and tools to analyze the outcomes of obsolescence management activities in terms of cost, schedule and performance. With its collective nature of all those guidebooks and handbooks for program managers, it represents a reference book for program managers for obsolescence management.

Even though there have been numerous studies sponsored by the US DoD, there is also an acute awareness of obsolescence on the other side of the Atlantic Ocean, in Europe. The UK Ministry of Defense (MoD) released its Defense Industrial Strategy in 2005. This strategy pays attention to obsolescence within its strategic goals and includes it in low level goals for each sub-industry and its capabilities such as Research and Technology, Innovation, System Engineering, Maritime, Air, Land (Great Britain 2005) .

## 3.2 Organizational and Industrial Studies on Obsolescence

As government-affiliated organizations' studies accumulated, we also observed studies conducted by service research labs such as the US Navy and Air Force Research Labs and the defense industry. In this section we will review those studies.

A Boeing report written by Porter demonstrates a method to find the optimum point in deciding whether to buy or redesign a part that is subject to obsolescence (Porter 1998). This study is one of the earliest ones to show the break-even point for either Last Time Buy Order or Redesign decisions; the reported helped generate a lot of following studies on this topic because of the many issues it raised.

Even though the study is limited to avionics equipment, the model can be used for other parts as well. Since the recertification process is highly expensive in avionics systems, obsolescence in particularly considered one of the most challenging problems in the industry.

The study is based on an optimum point between redesign costs and parts cost. The model is similar to the inventory EOQ model in which Holding Cost is replaced by Parts Costs and Setup Cost is replaced by Redesign Costs.

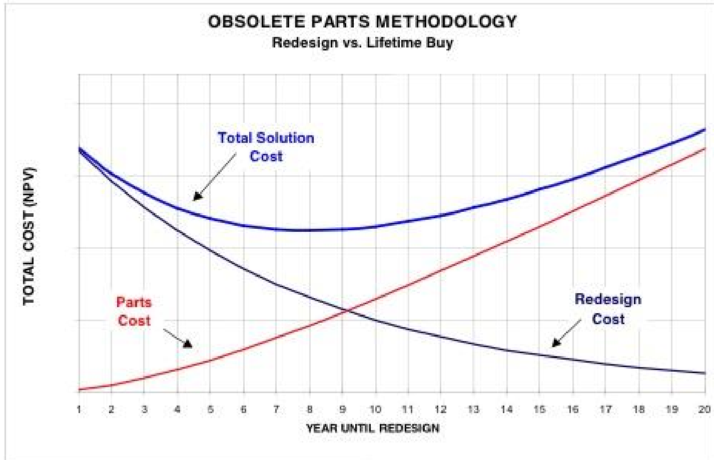


**Figure 1 Obsolete Parts Methodology of Porter (Porter 1998)**

The Electronics Parts Obsolescence Initiative (EPOI), a group established by the US Air Force, released a report in 1999 to offer a four step process; this process showed some numerical figures for the extended life of weapon systems, which only exacerbate the obsolescence problem of the military community (Stogdill 1999). EPOI defined four basic resolution alternatives in the study:

- Life-of-type buy,
- Part substitution,
- Redesign,
- Complete system redesign.

Based on these alternatives, Northrop Grumman showed that the redesign method for a radar card of the AWACS plane could save $15.1 million USD. Life-of-type buys were given as the easiest alternative; however predictions for future needs still remains a challenge. This was considered the least cost effective solution because of the high inventory cost of components that may never be used.

This study is one of the first ones that clearly state the three major components of contemporary obsolescence management strategy:

- The necessity of business case development and increased managerial awareness of obsolescence
- Design for obsolescence to include considerations of the whole life cycle cost of systems
- Long term agreements with subcontractors

Support for long-term agreements with contractors was seen as a crucial point in maintaining a system during its life; because of this dimension, it can be considered the early implementation of Performance Based Logistics Systems.

In addition to the EPOI's support tool, another decision support tool by the US Navy was released in 1999: The TEAM (Chestnutwood and Levin 1999).. The Technology Assessment and Management (TEAM) methodology is a decision support tool for program managers and it focuses on optimizing sustainment costs while inserting newer technology into systems. The TEAM approach is a combination of NAVSEA and NAVAIR obsolescence programs with specifically defined tools and processes.

In 2006, the US Navy released another study, which outlined the Technology Refresh for Navy Transformation (TRENT) methodology. TRENT program objectives are *"to improve the readiness, mission capability, and life-cycle affordability of Navy weapon systems through the development of a new enterprise-wide strategy for proactive technology management at the system level"*(Stavash et al. 2006). This methodology is a collection of processes depicted in Figure 2. The processes are forecasting, evaluation, selection, implementation and feedback.

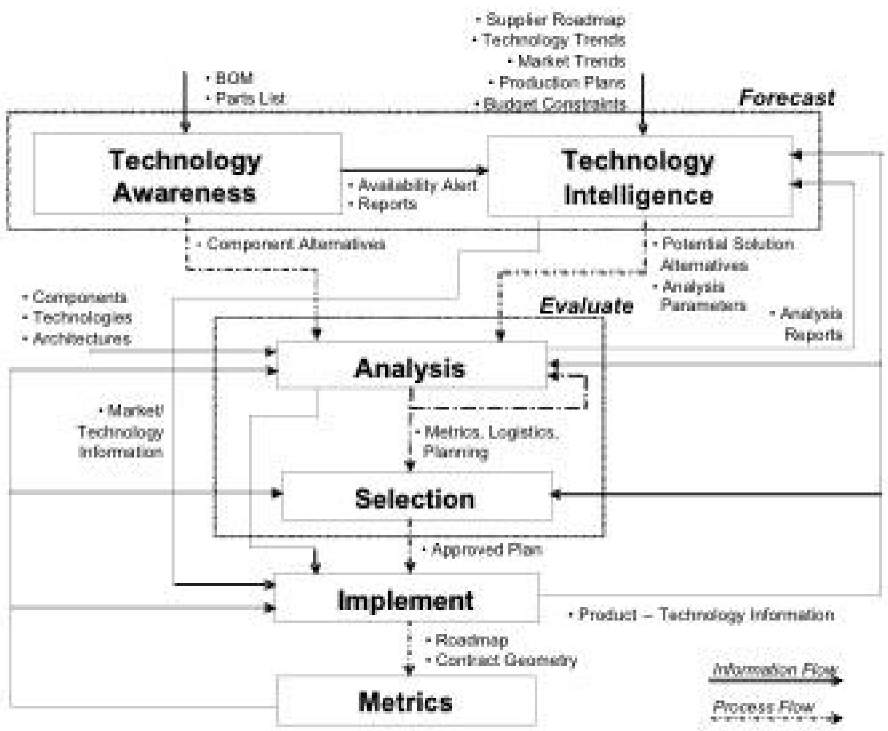


**Figure 2 TRENT Methodology (Stavash et al. 2006)**

## 3.3 Academic Studies on Obsolescence

Starting from 2000 onward, universities and academics became more involved in obsolescence studies whereas previously the major players were limited to the defense industry and defense organizations. Preliminary studies were about reactive obsolescence strategies and those strategies heavily relied on the recognition of obsolescence notification.

The most commonly used methods in military and commercial industries are Bridge Buy or Life-Time-Buy (LTB) (Feng 2007). How much for the procurement of a bridge buy or a LTB solution is a cost minimization problem. There are several proposed models which include individual buy models and life cycle cost minimization models. One of those models is based on the data mining of historical buys (P. Sandborn, Prabhakar, and Feng 2007). Another model is based on stochastic analysis and the Life of Type Evaluation (LOTE) tool was devised to optimize lifetime buy quantities by minimizing the lifecycle cost that take procurement cost, inventory cost, disposal cost, and penalty cost into account (Feng, Singh, and Sandborn 2007). This model shows resemblance to classical newsvendor problem and is an extension of the Fortuin model (Feng 2007). Fortuin's model also takes procurement, inventory, disposal, and penalty costs into account and was constructed on user defined time intervals as a discrete time optimization model (Teunter R.H. and Fortuin 1999). Uprating is another method used to combat obsolescence. With this method, a part is used outside the specification limits determined by the original manufacturer, especially in thermal limits (Pecht and Humphrey 2008). Piggybacking is also used against obsolescence and it "*enables renewed functionality of a technologically obsolete product through the integration or add-on of a secondary device or component*" (Rai and Terpenny 2008). Even though it is not directly linked to obsolescence, Kooten proposed a model to calculate final orders for repairable spare parts that was devised by using the transient Markov chain (Van Kooten and Tan 2007). Shen proposed a framework for selecting the most appropriate reactive technique among a subset of reactive methods (LOT Buy, Part Substitution and Line Redesign) till a design refresh date and forecasting the optimum time for design refresh (Shen and Willems 2014). A similar comparison was made by Sandborn for Life Time Buy and Bridge Buy to find optimum quantities to procure (P. Sandborn and Goudrazi 2015).

However, a better strategy for obsolescence is the proactive approach and it is one that necessitates forecasting obsolescence. One of the first studies to propose a forecasting model for the obsolescence zone ([mean+2stdDev - mean+3 stdDev]) used peak sale data for electronic parts and tried to forecast the life cycle based on that data (Solomon, Sandborn, and Pecht 2000). The same model was modified to include additional adjustments by adding the electronic part as a secondary attribute (P Singh et al. 2002)(Pameet; Singh and Sandborn 2006).

The obsolescence zone that was derived from a part's life cycle estimation based on peak sales data was augmented by a follow up study which uses an analytical approach (P. Sandborn, Mauro, and Knox 2007). The analytical approach takes market trends and technology into account and uses data mining based algorithms to forecast obsolescence dates with an increased accuracy. The combined approach gives a window of obsolescence based on a desired confidence level. The study proposes that better obsolescence forecast results only comes with continuous forecasting.

Josias proposed an obsolescence forecast model that uses multiple regression model (Josias, Terpenny, and McLean 2004). This model resembles the model of Sandborn in terms of the independent variables as they are similar to the attributes defined in the Sandborn model. The difference is that the latter used those attributes one after another. However in the Josias model, all the independent variables are used together. The dependent variable is the introduction date of the given part. This value is of no use directly but the study proposes to use that variable to derive obsolescence date indirectly.

Another model to uncover the End of Repair/Maintenance period with a discrete event simulation technique by using the existing inventory and future demands of a given systems parts was proposed by Konozo (A. J. Konoza 2012)(A. Konoza and Sandborn 2012)(A. Konoza and Sandborn 2013). This model takes into account inventory management terms such as inventory degradation, inventory inspection periods and inventory segregation.

Design refresh is "*the ultimate obsolescence mitigation approach where obsolete parts are designed out of the system in favor of newer, non-obsolete parts"* (P. Sandborn et al. 2002). In the case of sustainment-dominated systems, needing recertification or other additional costs such as documentation changes, design refresh comes with large non-recurring costs. Therefore the decision to initiate a design refresh necessitates careful planning. According to Plunket, a technology refreshment strategy is essential (Plunkett, Dinesh; Verma 2003). Proactive design and open system architecture is a MUST with standard commercial interfaces.

The difference between the Porter's (Porter 1998) approach and Sandborn's Design Refresh date selection approach is that, Porter compared only Last Time Buy reactive strategy to design refresh while Sandborn used more mitigation strategies in his tool, Mitigation of Obsolescence Cost Analysis (MOCA). The MOCA tool supports the obsolescence forecast functionality for each part in the system by using the primary and secondary attributes via part's life cycle. A part's life cycle is determined by using the statistical analysis on the peak sales data.

Figure 3 shows the design refresh planning analysis timeline. Every obsolescence problem, once notified, always starts with a reactive technique for short-term solutions. A design refresh activity is then planned for the longer term as a strategic level technique (P. Sandborn 2013).

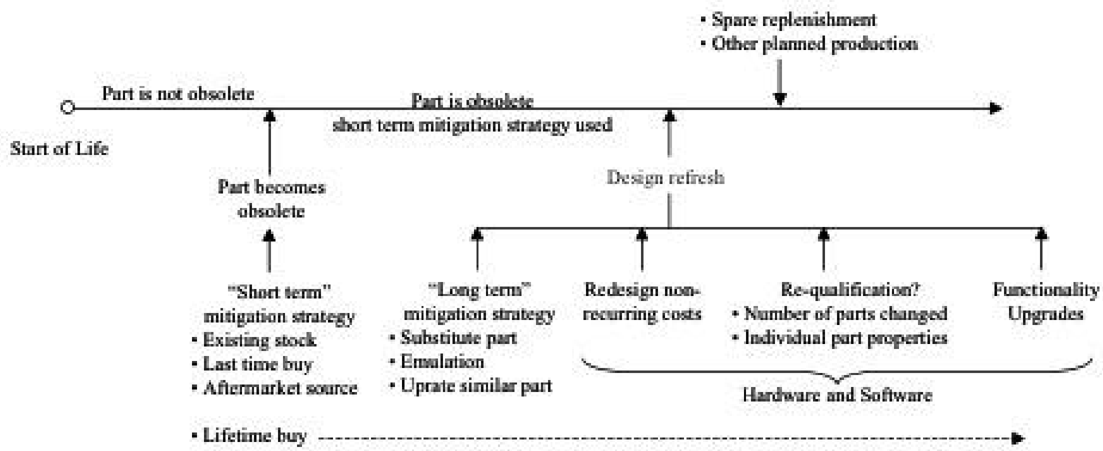


**Figure 3 Design Refresh Planning Analysis Timeline (P Singh et al. 2002)**

An extension to MOCA is added by constructing Bayesian Belief Networks on candidate design refresh dates (Pameet Singh, Sandborn, and Singh 2004). The Bayesian method is used to reason under uncertainty with subjective beliefs. Additionally, Zheng et.al. reiterates Sandborn's Design Refresh Model by using the Integer Programming method (Zheng, Terpenny, and Sandborn 2015).

Since redesign technique is considered to be an expensive method, Barton supports the idea of decreasing the number of redesigns by paying more attention to the specification phases of the program both in the analysis and design processes (Barton and Chawla 2003). However this approach is only valid for the waterfall development model. Especially for IT related projects, the waterfall development model is not advised anymore, instead, contemporary development models such as agile, iterative and incremental development models are favored and continuous redesign is a crucial part of agile development. However, it is also true that, minimizing the number of redesigns during the in-use period of the system by using certain proactive and strategic methods is necessary.

Kumar and Saranga proposed a model for program managers to select the best obsolescence mitigation strategy, namely design refresh model and Life-of-Type Buy selection (Kumar and Saranga 2008). However such models do not always provide efficient solutions if the remaining life of the system is long or the technology change rate is high. In such cases, Kumar proposed the multi-armed Bandit models. The Bandit models allocate scarce resources to competing selections when there is not much information during allocation period, however such information becomes more available as time passes. Bandit method in obsolescence management models provides a framework for program managers to make better decision as time passes and more information becomes available.

From a holistic point of view, obsolescence is also affiliated with integrated logistic systems (Marshall and Lambert 2008). Marshall's study asserts that the obsolescence problem is more heavily felt in sustainment dominated systems than others and therefore it needs to be taken into account in Integrated Logistic Systems and relevant solutions. Since DMSMS solutions are advised to be included in the contract terms, such approach can also be considered the precursor of Performance Based Logistics (PBL) models.

PBL transfers the burden of obsolescence mitigation responsibility to the contractor. In that case the estimation of the cost of obsolescence of parts inside a given system during the bidding period is a major concern for contractors. Certain models and frameworks are proposed to estimate obsolescence cost during bidding phase (Rojo et al. 2012) (Feldman and Sandborn 2007). The real solution resides in designing the system to obsolescence so that less reactive obsolescence management techniques need to be used (Feldman and Sandborn 2007). This necessitates the use of BOM and running this list against obsolescence forecasting methods that are followed by strategic obsolescence management techniques such as design refresh. As PBL takes greater attention of both contractors and state agencies, Sandborn proposed a model to incorporate a Public Private Partnership approach to the military PBL contracts that had produced successful results in civil infrastructure areas (P. Sandborn 2014). The model uses Petri-Nets as well as affine controller function points and can be used by both contractors and states to increase their mutual profits.

While considering reactive strategies, it would appear that the obsolescence problem could be reduced to the supply chain management problem. Second sourcing and hoarding among other reactive strategies are considered to be other ways of mitigating the probability of obsolescence (Prabhakar et al. 2013) (Prabhakar and Sandborn 2013).

Since the whole idea behind obsolescence management is to increase sustainability, Sandborn proposed the idea of using reactive, proactive and strategic management techniques together within a top level umbrella approach to minimize the life cycle costs of a given sustainment dominated system (P. A. Sandborn et al. 2003) (P. Sandborn 2008a). In order to evaluate the effectiveness of those techniques we have to measure them and Sandborn proposed to use viability to measure the sustainability.

Various studies on obsolescence management which include forecasting, necessitate a common language. Ontology based knowledge representation was proposed for parts, components, resolution techniques and forecasting to enable the integration of different techniques (Zheng 2011)(Zheng et al. 2013). Motivation for such a study is fully necessary however this study needs much more elaboration in the future.

Designing for obsolescence is a common approach to follow. Baker proposed using FPGA based technologies and emulating the system to scrape out the unused functionalities so as to make systems simpler (Baker 2013). He also asserts that providing that redesign meets same functionality, regression testing would be limited to mechanical and electrical testing. However, the most sustainment-dominated systems require a full regression test for even a minimal change to be made on the original design.

Cuculoski proposed a model based on the reliability and maintainability of a given system (Cuculoski 2013). He stressed the need for data and a proper analysis method performed by capable teams. The study reveals that if appropriate obsolescence management methodologies are followed, keeping the existing system would be more cost effective than acquiring a new system. However, he did not take the recertification cost of a redesigned system into account when comparing the cost of a new system to a redesigned one.

Studies on taking constraints into account (P. Sandborn, Terpenny, and Zheng 2011) in obsolescence management models are expanded upon in another study to turn implicit constraints into explicit ones (Nelson III and Sandborn 2013).

Rojo et.al. proposed a model to estimate the cost of component obsolescence (Rojo et al. 2012). The model takes "Obsolescence Management Levels", "Obsolescence Complexity Levels", "Resolution Profiles" and "Cost Metrics" into account and estimates the obsolescence cost for a given system in its service life. It also includes tools to provide assistance during the bidding process but prior to the contract awarding in the light of new climate of shifting obsolescence management activities to the contractor side within performance based logistics approach.

Raghavan's model calculates the life cycle cost, specifically for power plant components. It is a three step model that starts with the estimation of the failure rates of a given component followed by the estimation of the impact of obsolescence and preventative measures and ultimately end with cost calculation (Raghavan and Member 2012). The cost impact of obsolescence is considered a part of the whole life cycle cost of a given system. The same model was improved by adding state diagrams and utilizing the Monte Carlo simulation as well as using a modified Markov Chain approach (Raghavan, Chowdhury, and Member 2015).

Meng utilized the Last Time Buy and redesign techniques to find the minimum obsolescence cost (Meng, Thörnberg, and Olsson 2014) by devising a mathematically strategic and proactive model to find the minimum cost for system obsolescence management cost. The model is composed of two parts: graph model and optimization model. The graph model creates a data table to be used by the optimization model. The optimization model uses MILP by making use of transshipment model.

Obsolescence management is a multi-dimensional problem and all studies so far have considered the various aspect of subsets of the problem. The first study to draw attention of obsolescence management problem from a multi-criteria decision making view is prepared by Pingle (Pingle 2015).

## 4.0 REVIEW METHOD AND PROCEDURES

We have conducted this review by reviewing about 300 papers from various databases starting from the 1960s up to today. The keywords used for the research were: "Obsolescence", "Obsolescence Management", "Product Life Cycle Cost Management", "Sustainment Dominated Systems" and "COTS in Military Systems". Various databases such as "IEEE Explore", "Engineering Village" and "Science Direct" as well as various search tools were used in this review.

All papers, proceedings, article magazines were screened based on their abstracts and non-relevant ones were discarded. The remaining sources were forward and backwards checked for additional references which were not discovered in the initial search. At the end, all references were clustered based on the following themes: "Acquisition and Logistic Models", "COTS and its effects on Obsolescence", "Electronic Part Obsolescence", "Software Obsolescence", "Obsolescence Mitigation Model", "Design Refresh Planning, "Forecasting Models", "Obsolescence Management Tools", "Obsolescence Management Plan". Each cluster of references was further analyzed in detail. Following the detailed analysis of the references, we grouped the studies into three main clusters by chronological order.

## 5.0. RESULTS

The studies on obsolescence management started towards the end of the 20th century; this coincided with the end of the Cold War and a shift in the industry to a focus on consumer electronics with shorter product life cycles. Sustainment-dominated system industries had to adapt to the new era and designs for such systems with longer product life cycles increasingly embraced low cost shorter life cycle system components. Fast technological speed and frequent changes in consumer needs exacerbated the obsolescence problem for sustainment-dominated systems.

The US Department of Defense first recognized the obsolescence problem and initiated actions and stimulated motivation to conduct studies on obsolescence. The findings of preliminary studies outlined how failing to manage obsolescence properly would put a huge burden on maintenance agencies. Later on, both the military and aerospace industries released papers to increase the awareness of the obsolescence problem as they had already begun to be impacted by it. While most of the papers were limited to outlining the problems, some of them also proposed solutions. Around the same time industry papers came out, academic research studies also began in both universities and institutions.

Most of the preliminary strategies on obsolescence management concerned reactive solutions. Later studies showed that proactive approaches would yield much more cost effective solutions. Follow up studies focused on data collection and analyzing data to forecast future demand as well as to predict obsolete parts in order to bring up a more cost effective solution with a proactive strategy. Finally, most contemporary strategies yield a holistic approach to include many other aspects of the overall obsolescence problem including procurement models, design methodology, supply chain systems, stakeholder management, logistic systems, and development models.

As the awareness of obsolescence has increased globally, specific workshops and conferences are held on the topic; additionally, portals on obsolescence are widely available for individuals and organizations to share information on this topic.

## 6.0. CONCLUSIONS

Obsolescence is a major problem for systems with a long product life; this problem has to be addressed and managed. Lack of management and poor planning for obsolescence causes companies and governments to spend progressively more of their budgets to deal with aging systems.

The US Government and DoD seem to be the most obsolescence aware organizations. As the obsolescence problem is much more recognized, the US government has funded new agencies to work on obsolescence as well as added new tasks to existing agencies. However, not every government, especially in developing countries, has achieved such awareness and it is still a major problem for the sustainability of systems in such nations.

Various models have been proposed to manage and mitigate the obsolescence problem from different aspects. Each model tries to convert the problem into a known problem type. We have observed different solutions including regression models, discrete time event simulation, constrained optimization models, integer programing, multi-criteria decision-making models, data mining as well as others.

With increased awareness, obsolescence management can and will be a part of the focus areas for government procurement and maintenance agencies for sustainment dominated systems. Even though PBL-like systems seem to be viable solutions, naturally they do not solve the entire problem. Therefore, developing countries, which primarily focus on aggressive acquisition, need to pay adequate attention to the planning and management of obsolescence.

## 7.0 BIBLIOGRAPHY

Baker, Alan. 2013. "Configurable Obsolescence Mitigation Methodologies." In *2nd International Through-Life Engineering Services Conference*, 11:352–56. Elsevier B.V. doi:10.1016/j.procir.2013.07.013.

Bartels, Bjoern, Ulrich Ermel, Michael Pecht, and Peter Sandborn. 2012. *Strategies to the Prediction, Mitigation and Management of Product Obsolescence*. *John Wiley & Sons, Inc.* doi:10.1002/9781118275474.

Barton, D.L., and P. Chawla. 2003. "Designing Systems for Future Obsolescence." In *Digital Avionics Systems Conference, 2003. DASC '03. The 22nd*, 2:1–11. doi:10.1109/DASC.2003.1245938.

Chestnutwood, Mark, and Ron Levin. 1999. "Technology Assessment and Management Methodology-an Approach to System Life Sustainment and Supportability Enhancement." In *Gateway to the New Millennium. 18th Digital Avionics Systems Conference. Proceedings (Cat. No.99CH37033)*, C.2-7 vol.:1.A.3–1 – 1.A.3–8. IEEE. doi:10.1109/DASC.1999.863678.

Cuculoski, Vlatko. 2013. "Obsolescence Management of Electronic and Control Systems." In *Australian Control Conference*, 342–47. Perth.

Defense Standardization Program Office. 2016. *Diminishing Manufacturing Sources and Material Shortages (SD-22) 2016*.

Department of Defence. 1994. *Military Handbook*. *Department of Defence*.

Department of Defense. 2003. "A Guide to Increased Reliability and Reduced Logistics Footprint."

Department of Defense. 2004a. "Performance Based Logistics A Program Manager's Product Support Guide." *Usawc Strategy Research Project*. doi:10.1007/978-3-8349-3726-1.

Department of Defense. 2004b. "Product Support Boundaries."

Department of Navy. 2005. "Diminishing Manufacturing Sources and Material Shortages Management Plan." Office of the Assistant Secretary of the Navy.

Feldman, Kiri, and Peter Sandborn. 2007. "Integrating Technology Obsolescence Considerations into Product Design Planning." In *International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, 1–8. doi:10.1115/DETC2007-35881.

Feng, Dan. 2007. "Optimizing Lifetime Buy Quantities to Minimize Lifecycle Cost."

Feng, Dan, Pameet Singh, and Peter Sandborn. 2007. "Lifetime Buy Optimization to Minimize Lifecycle Cost." In *Proceedings of the 2007 Aging Aircraft Conference*. http://www.enme.umd.edu/ESCML/Papers/AgingAircraft07-LTB.pdf.

Great Britain. 2005. "Defence Industrial Strategy." *Defence Studies*. Vol. 8. doi:10.1080/14702430802252545.

Haines, Linda. 2001. "Technology Refreshment Within DoD."

Hitt, E.F., and J. Schmidt. 1998. "Technology Obsolescence (TO) Impact on Future Costs." In *17th DASC. AIAA/IEEE/SAE. Digital Avionics Systems Conference. Proceedings (Cat. No.98CH36267)*. Vol. 1. doi:10.1109/DASC.1998.741445.

Josias, Craig, Janis P Terpenny, and Kenneth J. McLean. 2004. "Component Obsolescence Risk Assessment." In *Proceedings of the 2004 Industrial Engineering Research Conference (IERC)*, 15:2–7. http://www.enme.umd.edu/ESCML/ObsSGER/IERC2004-Josias-Terpenny-McLean-376.pdf.

Koch, Robert, and Gabi Dreo Rodosek. 2012. "The Role of COTS Products for High Security Systems." In *2012 4th International Conference on Cyber Conflicts*, 413–26.

Konoza, Anthony Joseph. 2012. "An Evaluation of End of Maintenance Dates and Lifetime Buy Estimations for Electronic Systems Facing Obsolescence."

Konoza, Anthony, and Peter Sandborn. 2012. "An Evaluation of End of Maintenance Dates for Electronic Assemblies." In *Aircraft Airworthiness & Sustainment Conference*.

Konoza, Anthony, and Peter Sandborn. 2013. "Evaluating the End of Maintenance Dates for Electronic Assemblies Composed of Obsolete Parts." *MEchanical Design*, 1–35.

Kumar, Dinesh, and Haritha Saranga. 2008. "Optimal Selection of Obsolescence Mitigation Strategies Using a Class of Bandit Models." Vol. 26993130.

Marshall, Maria M., and Keith R. Lambert. 2008. "Insights into Supporting Complex Systems under Conditions of Obsolescence." In *PICMET: Portland International Center for Management of Engineering and Technology, Proceedings*, 1918–23. doi:10.1109/PICMET.2008.4599811.

McDermott, Jack; Jennifer Shearer; Walter Tomczykowski. 1999. "Final Report, Resolution Cost Factors for Diminishing Manufacturing Sources and Material Shortages."

Meng, Xiaozhou, Benny Thörnberg, and Leif Olsson. 2014. "Strategic Proactive Obsolescence Management Model." *IEEE Transactions on Components and Packaging and Manufacturing Technologies* 4 (6): 1099–1108.

Nelson III, Raymond S, and Peter Sandborn. 2013. "Strategic Management of Component Obsolescence Using Constraint-Driven Design Refresh Planning." *International Journal of Product Lifecycle Management* 6 (2): 99–120. doi:http://dx.doi.org/10.1504/IJPLM.2012.052656.

Pecht, M G, and D Humphrey. 2008. "Addressing Obsolescence - The Uprating Option." *IEEE Transactions on Components and Packaging Technologies* 31 (3): 741–45. ISI:000259573600026.

Pertowski, Thaddeus, and Chris Denham. 1998. "Approaches to Reduce Impact of Electronic Component Obsolescence Component Information Management System." In *Proceedings of the Annual IEEE International Frequency Control Symposium*, 430–38. http://www.scopus.com/inward/record.url?eid=2-s2.0-0032320362&partnerID=40&md5=9bea4255b6a34b4d41bdb86948d45e24.

Pingle, Pratik. 2015. "Selection of Obsolescence Resolution Strategy Based on a Multi Criteria Decision Model." Iowa State University.

Plunkett, Dinesh; Verma, Galen. 2003. "Technology Refreshment and Obsolescence Avoidance Strategy and Plan."

Porter, Zell. 1998. "An Economic Method for Evaluating Electronic Component Obsolescence Solutions." *Boeing Information Space & Defence Systems*, 1–9. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:An+Economic+Method+for+Evaluating+Electronic+Component+Obsolescence+Solutions#0.

Prabhakar, Varun J, and Peter Sandborn. 2013. "A Model for Comparing Sourcing Strategies for Parts in Long Life Cycle Products Subject to Long-Term Supply Chain Disruptions." *International Journal of Product Lifecycle Management* 6 (3): 228–49.

Prabhakar, Varun J., Hannah Allison, Peter Sandborn, and Bo Eriksson. 2013. "Optimizing Part Sourcing Strategies for Low-Volume, Long Life Cycle Products Using Second Sourcing Ad Part Hoarding." In *INTERNATIONAL DESIGN ENGINEERING TECHNICAL CONFERENCES*.

Raghavan, Srinath, Badrul Chowdhury, and Senior Member. 2015. "State Diagram-Based Life Cycle Management Plans for Power Plant Components." In *IEEE Transactions on Smart Grid*, 6:965–72.

Raghavan, Srinath, and Student Member. 2012. "Developing Life Cycle Management Plans For Power Plant Components." In *North American Power Symposium (NAPS), 2012*.

Rai, Rahul, and Janis Terpenny. 2008. "Product Obsolescence." *Ieee Transactions on Components and Packaging Technologies* 31 (4): 880–89. doi:10.1109/TCAPT.2008.2005115.

Rajagopal, S., J.A. Erkoyuncu, and R. Roy. 2015. "Impact of Software Obsolescence in Defence Manufacturing Sectors." In *3rd CIRP Global Web Conference Impact*, 28:197–201. doi:10.1016/j.procir.2015.04.034.

Rojo, F. J. Romero, Rajkumar Roy, Essam Shehab, Kalyan Cheruvu, and P. Mason. 2012. "A Cost Estimating Framework for Electronic, Electrical and Electromechanical (EEE) Components Obsolescence within the Use-Oriented Product-Service Systems Contracts." In *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 226:154–66. doi:10.1177/0954405411406774.

Romero Rojo, Francisco Javier, Rajkumar Roy, and Essam Shehab. 2009. "Obsolescence Management for Long-Life Contracts: State of the Art and Future Trends." *International Journal of Advanced Manufacturing Technology* 49 (9-12): 1235–50. doi:10.1007/s00170-009-2471-3.

Sandborn, Peter. 2007. "Designing for Technology Obsolescence Management." In *Industrial Engineering Research Conference*.

Sandborn, Peter. 2008a. "Strategic Management of DMSMS in Systems." *DSP Journal*, no. June: 24–30.

Sandborn, Peter. 2008b. "Trapped on Technology's Trailing Edge." *IEEE Spectrum*.

Sandborn, Peter. 2013. "Design for Obsolescence Risk Management." In *2nd International Through-Life Engineering Services Conference Design*, 11:15–22. Elsevier B.V. doi:10.1016/j.procir.2013.07.073.

Sandborn, Peter. 2014. "A New ‘ Availability-Payment ’ Model for Pricing Performance-Based Logistics Contracts."

Sandborn, Peter A., Thomas E. Herald, James Houston, and Pameet Singh. 2003. "Optimum Technology Insertion into Systems Based on the Assessment of Viability." *IEEE Transactions on Components and Packaging Technologies* 26 (4): 734–38. doi:10.1109/TCAPT.2003.820984.

Sandborn, Peter, and Navis Goudrazi. 2015. "A Real Options Approach to Quantity and Cost Optimization for Lifetime and Bridge Buys of Parts." In *Acquisition Research Symposium*.

Sandborn, Peter, Frank Mauro, and Ron Knox. 2007. "A Data Mining Based Approach to Electronic Part Obsolescence Forecasting." *IEEE Transactions on Components and Packaging Technologies on Components and Packaging Technologies* 30 (3): 397–401.

Sandborn, Peter, Varun Prabhakar, and Dan Feng. 2007. "DMSMS Lifetime Buy Characterization Via Data Mining of Historical Buys." In *DMSS Conference*. University of Maryland. http://www.enme.umd.edu/ESCML/obsolescence.htm.

Sandborn, Peter, Pameet Singh, Todd Geiser, and David Lorenson. 2002. "Electronic Part Obsolescence Driven Product Redesign Optimization." *International Journal of Advanced Manufacturing Systems* 7 (2): 1–13. http://www.enme.umd.edu/ESCML/Papers/AgingAircraft.pdf.

Sandborn, Peter, Janis P Terpenny, and Liyu Zheng. 2011. "Modeling Constraints in Design Refresh Planning." In *ASME 2011 International Design Engineering Technical Conferences*, 1–11. Washington DC: ASME. doi:DETC2011-47644.

Shen, Yuelin, and Sean P. Willems. 2014. "Modeling Sourcing Strategies to Mitigate Part Obsolescence." *European Journal of Operational Research* 236 (2): 522–33. doi:10.1016/j.ejor.2014.01.025.

Singh, P, P Sandborn, D Lorenson, and T Geiser. 2002. "Determining Optimum Redesign Plans for Avionics Based on Electronic Part Obsolescence Forecasts." In *World Avioation Congress and Exposition*. doi:10.4271/2002-01-3012.

Singh, Pameet, P. Sandborn, and Pameet Singh. 2004. "Forecasting Technology Insertion Concurrent with Design Refresh Planning for COTS-Based Electronics Systems." *Logistics Spectrum* 38 (2): 349–54. doi:10.1109/RAMS.2005.1408387.

Singh, Pameet;, and Peter Sandborn. 2006. "Obsolescence Driven Design Refresh Planning for Sustainment-Dominated Systems." *The Engineering Economist* 51 (2): 115–39.

Solomon, Rajeev, Peter A. Sandborn, and Michael G. Pecht. 2000. "Electronic Part Life Cycle Concepts and Obsolescence Forecasting." *IEEE Transactions on Components and Packaging Technologies* 23 (4): 707–17. doi:10.1109/6144.888857.

Stavash, Jeffrey, Shanti Sharma, Thad Konicki, and Cherry Hill. 2006. "Technology Refresh A System Level Approach to Managing Obsolescence." In *Engineering for Affordability*, 1–5.

Stogdill, Ronald C. 1999. "Dealing with Obsolete Parts." *IEEE Design and Test of Computers* 16 (2): 17–25. doi:10.1109/54.765200.

Teunter R.H., and L. Fortuin. 1999. "End-of-Life Service." *International Journal of Production Economics*

59: 487–97.

Tomczykowski, Walter, Anton Fritz, and Ray Scalia. 2001. "Common Practices to Mitigate the Risk of Obsolescence."

Turkey, SSM. 2012. "2012-2016 Stratejik Plani." Vol. 53. doi:10.1017/CBO9781107415324.004.

United States Coast Guard. 2012. "Diminishing Manufacturing Sources and Material Shortages Manual." http://www.dmea.osd.mil/docs/sd22dmsms_Guidebook.pdf.

USA. 2000. "Commercial Of The Shelf Policy." US Department of Teh Navy.

Van Kooten, John P.J., and Tarkan Tan. 2007. "The Final Order Problem for Repairable Spare Parts under Condemnation." *Operations Research Society* 53 (9): 1689–99. doi:10.1017/CBO9781107415324.004.

Weiss, Herbert K. 1961. "Weapon System Phasing for Ready Forces." *IRE Transactions on Engineering Management* EM-8 (1): 30–34. doi:10.1109/IRET-EM.1961.5007581.

Zheng, Liyu. 2011. "Knowledge Representation and Decision Support for Managing Product Obsolescence." *ProQuest Dissertations and Theses*. http://search.proquest.com/docview/1020897067?accountid=14511\nhttp://sfx.ucl.ac.uk/sfx_local?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations+&+theses&sid=ProQ:ProQuest+Dissertations+&+Theses+Global&atitle=&title=Know.

Zheng, Liyu, Raymond Nelson, Peter Sandborn, and Janis P Terpenny. 2013. "Ontology-Based Knowledge Representation for Obsolescence Forecasting." *Journal of Computing and Information Science in Engineering* 13. doi:10.1115/1.4023003.

Zheng, Liyu, Janis Terpenny, and Peter Sandborn. 2015. "Design Refresh Planning Models for Managing Obsolescence." *IIE Transactions* 47 (12): 1407–23. doi:10.1080/0740817X.2014.999898.