Chapter 12
Sustainment Strategies for System Performance Enhancement

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Abstract "Sustainment" (as commonly defined by industry and government) is comprised of maintenance, support, and upgrade practices that maintain or improve the performance of a system and maximize the availability of goods and services while minimizing their cost and footprint or, more simply, the capacity of a system to endure. System sustainment is a multitrillion-dollar enterprise, in government (infrastructure and defense) and industry (transportation, industrial controls, data centers, and others). Systems associated with human safety, the delivery of critical services, important humanitarian, and military missions and global economic stability are often compromised by the failure to develop, resource, and implement effective long-term sustainment strategies. System sustainment is, unfortunately, an area that has traditionally been dominated by transactional processes with little strategic planning, policy, or methodological support. This chapter discusses the definition of sustainment and the relationship of sustainment to system resilience, the economics of sustainment (i.e., making business cases to strategically sustain systems), policies that impact the ability to sustain systems, and the emergence of outcome-based contracting for system sustainment.

Keywords Sustainment · Cost · Business case · Policy · Complex systems · Maintenance · System health management

12.1 Introduction

Sustainability and its variants have captured the interest of engineering (and other disciplines) for several decades. Even though sustainability and sustainment are sometimes used interchangeably, these words have unique connotations that depend on discipline in which they are used. The focus of this chapter is on the sustainment of complex engineered systems, but let us first look at the most prevalent usages of sustainment [1].

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Environmental sustainability is "the ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time" [2]. The objective of environmental sustainability is to increase energy and material efficiencies, preserve ecosystem integrity, and promote human health and happiness through design, economics, manufacturing, and policy.

Economic (business or corporate) sustainability refers to an increase in productivity (possibly accompanied by a reduction of consumed resources) without any reduction in quality or profitability. Business sustainability is often described as the triple bottom line [3]: financial (profit), social (people), and environmental (planet). "Sustainable operations management" integrates profit and efficiency with the stakeholders and resulting environmental impacts [4].

Social sustainability is the ability of a social system to indefinitely function at a defined level of social wellbeing [5]. Social sustainability has also been defined as "a process for creating sustainable, successful places that promote wellbeing, by understanding what people need from the places they live and work" [6]. Social sustainability is a combination of the physical design of places that people occupy with the design of the social world, i.e., the infrastructure that supports social and cultural life.

Technology or system sustainment refers to the activities undertaken to: (a) maintain the operation of an existing system (ensure that it can successfully complete its intended purpose), (b) continue to manufacture and field versions of the system that satisfy the original requirements, and (c) manufacture and field revised versions of the system that satisfy evolving requirements [7]. The term "sustainment engineering" when applied to technology sustainment activities is the process of assessing and improving a system's ability to be sustained by determining, selecting, and implementing feasible and economically viable alternatives [8].

Many specialized uses of sustainability exist,[1] which overlap into one or more of the categories above, including urban sustainability, sustainable living, sustainable food, sustainable capitalism, sustainable buildings, software sustainment, sustainable supply chains, and many others. Technology and system sustainment is the topic of this chapter (starting in Sect. 12.3).

12.2 A General Sustainment Definition

With so many diverse interests using sustainability/sustainment terminology, sustainment can imply very different things to different people. Both sustainment and sustainability are nouns. However, sustainment is the act of sustaining something, i.e., determination and execution of the actions taken to improve or ensure a system's

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[1] There are other usages that are not particularly relevant to engineered systems, for example, sustainment and sustainability are used as a general programmatic/practice metric; "sustainability" is a term used to refer to what happens after initial implementation efforts (or funding ends) where sustainability measures the extent, nature, or impact of adaptations to the interventions or programs once implemented, e.g., in health care [9].

longevity or survivability; while sustainability is the ability to sustain something or a system's ability to be sustained. Today, *sustain* is defined as keeping a product or system going or to extend its duration [10]. The most common modern synonym for *sustain* is *maintain.* S*ustain* and *maintain* may be used interchangeably, however, maintaining most often refers to actions taken to correct problems, while sustaining is a more general strategic term referring to the management of the evolution of a system. Basiago [11] points out that sustainability is closely tied to *futurity*; meaning renewed or continuing existence in a future time. To sustain embraces a philosophy in which principles of futurity guide current decision-making.

The first use of the word sustainability in the context of man's future was in 1972 [12, 13], and the term was first used in a United Nations report in 1978 [14]. For the history of the origin and development of socioecological sustainability, see, Refs. [15, 16]. The best-known socioecological definition of sustainability (attributed to the "Brundtland Report" [17]) is commonly paraphrased as "development that meets the needs of present generations without compromising the ability of future generations to meet their own needs." While the primary context for this definition is environmental (and social) sustainability, it has applicability to other types of sustainability. In the case of technology sustainment if the word "generations" is interpreted as the operators, maintainers, and users of a system, then the definition could be used to describe technology sustainment. Unfortunately, the concept of sustainability has been coopted by various groups to serve as a means-to-an-end in the service of special interests and marketing.

At the other end of the spectrum, the US Department of Defense (DoD) defines sustainment as "the provision of logistics and personnel services necessary to maintain and prolong operations through mission accomplishment and redeployment of the force" [18]. Sustainment provides the necessary support to operational military entities to enable them to perform their missions. The second, and perhaps more germane defense definition, is in the systems acquisition context. Once a system is developed and deployed the system operations and support phase consists of two major efforts "sustainment and disposal." How do these definitions relate to the design and production of systems? For many types of critical systems (systems that are used to ensure the success of safety, mission, and infrastructure critical activities), sustainment must be part of the initial system design (making it an afterthought is a prescription for disaster—see Sect. 12.3).

In 1992, Kidd [15] concluded that "The roots of the term 'sustainability' are so deeply embedded in fundamentally different concepts, each of which has valid claims to validity, that a search for a single definition seems futile." Although Kidd was only focused on socioecological sustainability, his statement carries a kernel of truth across the entire scope of disciplines considered in this chapter. Nonetheless, in an attempt to create a general definition of sustainment that is universally applicable across all disciplines, we developed the following. The best short definition of sustainment is the capacity of a system to endure. A potentially better, but longer, definition of sustainment was proposed by Sandborn [19]: "development, production, operation, management, and end-of-life of systems that maximizes the availability of goods and services while minimizing their footprint”. The general applicability of this definition is embedded in the following terms:

- “footprint” represents any kind of impact that is relevant to the system’s customers and/or stakeholders, e.g., cost (economics), resource consumption, energy, environmental, and human health;
- “availability” measures the fraction of time that a product or service is at the right place, supported by the appropriate resources, and in the right operational state when the customer requires it;
- “customer” is a group of people, i.e., individual, company, geographic region, or general population segment.

This definition is consistent with environmental, social, business, and technology/system sustainment concerns.

12.3 The Sustainment of Critical Systems

Having discussed the general sustainment/sustainability landscape, we now focus on technology/system sustainment, which is the topic of the remainder of this chapter. In this section, we define the type of “systems” we are concerned with and then describe what the sustainment of these systems entails.

Critical systems perform safety-, mission-, and infrastructure-critical activities that create the transportation, communications, defense, financial, utilities, and public health backbone of society.[2] The cost of the sustainment of these systems can be staggering. For example, the global maintenance, repair, and overhaul (MRO) market for airlines is expected to exceed $100B per year by 2026 [20]. Amtrak has estimated its capital maintenance backlog (which includes physical infrastructure and electromechanical systems) in the US Northeast Corridor, alone, at around $21 billion [21]. The annual cost to operate and maintain the Department of Defense vast sustainment enterprise was over $170B in 2011 [22]. The sustainment of critical systems encompasses all the elements in Table 12.1.

While it is easy to map the disciplines listed in Table 12.1 onto managing hardware components and subsystems, sustainment is more than hardware. Critical systems are composed of combinations of: hardware, software, operational logistics, business models, contract structures, and applicable legislation, policy and governance. If any of these system elements fails, the system potentially fails. The term “system resilience,” which is the intrinsic ability of a system to resist disruptions, i.e., it is its ability to provide its required capability in the face of adversity, in part encompasses sustainment. In the case of sustainment, we are concerned with adversity from

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[2] Another term for these systems is “mission critical”. These systems often become “legacy” systems because their field life is so long that during the majority of their life they are based on, or are composed of, out-of-date (old) processes, methodologies, technologies, parts, and/or application software.

Table 12.1 Elements of critical system sustainment

Affordability	Availability	Policy/governance	Mission engineering
Cost–benefit analysis	Readiness	System health management	Modernization/technology insertion
Warranty	Reliability	Upgradability	Logistics[a]
Maintainability	Obsolescence	Open systems	Outcome-based contracts
Viability	Prognostics	Qualification/certification	Sparing
Risk	Testability	Counterfeit management	
Diagnosability	Workforce	Configuration control	

[a] In [18], sustainment is distinguished from logistics, which is "supply, maintenance operations, deployment and distribution, health service support (HSS), logistic services, engineering, and operational contract support"

"aging" issues, both technological and nontechnological. The subsections that follow highlight some less obvious complex system sustainment issues.

12.3.1 Software Sustainment

All of the discussion so far can be readily applied to hardware, but sustainment also applies to software (and obviously, systems composed of both hardware and software). In the case of hardware, when a component fails, maintenance personnel can remove the failed component and replace it with a working component. The resolution to a software failure is less straightforward. First, the term "software failure" is more nebulous, and may mean that latent defects ("bugs") in the software have been encountered during operation, that the software has become incompatible with the system it is in due to other software or hardware changes to that system, or a host of other negative system impacts caused by the software, [23].

12.3.2 Operational Logistics—Supply Chain Sustainment

The supply chains for complex systems are becoming increasingly volatile and difficult to manage. Consider the F-35 Joint Strike Fighter aircraft, which partners with more than 1200 domestic suppliers and nine "partner countries" to produce "thousands of components from highly sophisticated radar sensors to the aircraft's mid fuselage" [24]. The F-35 manufacturing will continue until at least the mid-2020s and the aircraft must be maintained (i.e., spared) for the next 30+ years; how do you manage the F-35′s complex, multinational supply chain for those 30+ years so that you can keep the aircraft flying?

In short, supply chain sustainment involves managing supply chain risk over potentially long periods of time. This involves the management of sourcing, existing inventories, and disruptions to the supply chain. Unlike cell phones, for example, critical systems generally do not control the supply chain for their components, i.e., the supply chain does not exist for (and is not driven by) the critical system application. Many practices from high-volume industries (e.g., just-in-time and lean inventories), which were created to improve the efficiency of supply chains have increased the supply chain's "brittleness" and, consequently, an enterprise's exposure to supply disruptions [25]. Developing additional sources of supply can help reduce risks, but having them does not necessarily reduce supply chain vulnerabilities. Better options to reduce vulnerabilities may be available by working with the existing suppliers, e.g., using dual sites to assure supply at one site should a disaster strike the other, or making sure that suppliers have plans to address a wide variety of contingencies. Mission, safety, and infrastructure critical systems can complicate support because they require more sophisticated testing to ensure that all system interfaces are properly functioning. Budget constraints coupled with the increasing costs of new systems and personnel are increasing pressure to reduce the physical size of and budgets for support infrastructure.

12.3.3 Operational Logistics—Workforce Sustainment

The sustainment of critical systems is also impacted by the loss of critical human skills that either cannot be replaced or take impractically long times to reconstitute. Critical skills loss [26] becomes a problem for sustaining systems that depend on an aging workforce that has highly specialized, low-demand skills. Critical skills loss occurs when skilled workers retire and there is an insufficient number of younger workers to take their place. This does not occur because of inactivity, poor planning, or a lack of foresight by an organization. Rather, it is simply an inevitable outcome of the dependence on low-demand specialized skills. System sustainment challenges resulting from the loss of critical human skills have been reported in industries that include healthcare, nuclear power, and aerospace. An example is the shortage of mainframe application programmers that are experienced in legacy applications—in this case, the required skills are no longer taught as part of any structured educational program and younger workers are not interested in learning them. For critical systems, the problems can be devastating: "Even a 1-year delay in funding for CVN-76 [aircraft carrier] will result in the loss of critical skills which will take up to 5 years to reconstitute through new hires and training. A longer delay could cause a permanent loss in the skills necessary to maintain our carrier force" [27].

12.3.4 Contract Structure

The long-term contract structures under which critical systems are delivered and supported play an increasingly critical role in defining the strategies that govern how sustainment is performed. In addition to a legacy transactional approach, there are a group of strategies for system support is called outcome-based logistics or contracting (also referred to as "performance contracting," "availability contracting," "contract for availability (CfA)," "performance-based service acquisition (PBSA)," "performance-based logistics (PBL)," and "performance-based contracting"). In outcome-based contracting, a contractor delivers performance outcomes that are defined by performance metric(s) for a system instead of delivering a particular good or service. The mindset behind outcome-based contracts is well summarized by Levitt [28] as, "The customer doesn't want a drilling machine; he wants a hole-in-the-wall." Outcome-based contracts pay the contractor for effectiveness (which can be articulated as availability, readiness, or other performance-related measures) at a fixed rate, penalizing shortcomings in the effectiveness delivered, and/or awarding gains beyond the target goals.

Outcome-based contracting exists because customers that require high availability systems are interested in buying system (in some cases subsystem or component) availability, rather than buying the system. For this type of contract, the customer pays for the outcome delivered, instead of buying the system and paying for system sustainment. Outcome-based contracts include cost penalties for failing to meet specified availability and performance requirements during defined time periods.

Outcome-based contracts make the sustainment community responsible for designing systems (including designing the sustainment of systems) and to coordinate the system design and the design of the contract terms. "For systems managed under outcome-based contracts, contract failure may mean significant money is spent by the customer (potentially the public) for either no outcome or inadequate outcome, or result in the contractor being driven out of business, which can lead to disaster for both parties" [29].

12.3.5 Governance and Policy

When designing and producing complex systems, there are host of technical challenges that must be resolved to meet their sustainment requirements. Although, resolving these engineering issues is necessary, it is generally insufficient to meet these requirements. Most critical systems operate at the intersection of the public and private sectors, where their sustainment is subject to a host public policy as well as business considerations. Moreover, during this era of disruptive technical developments, government policies and business models lag and may in fact impede the use of innovative sustainment practices and processes.

The US DoD, for example, has a host of legislative and regulatory policies that must be considered when performing sustainment tasks. These include legislation that specifies the definition of organic depot maintenance,[3] types and amounts of work that must be performed there, along with guidance on how these depots can form public–private partnerships—these all constrain the sustainment solutions space. Federal acquisition regulations provide detailed guidance on acquisition planning and awarding contracts. There are also a myriad of Department, Military Service, and Agency instructions and regulations that provide guidance on every level of maintenance, supply, and transportation operations. Contracts, for example, maybe restricted in terms of type and contract length, potentially limiting the benefits of outcome-based contracting.

Business models are also fundamentally connected to, and informed by, technological innovation. They serve as the intermediary link between traditional firm performance and operation, enabling firms and organizations to leverage the benefits that technology can offer. As the role of technology increasingly affects the production, supply chains, and system sustainment, these innovations will necessitate changes to the existing business models, particularly as these businesses transition into the digital era. To adapt, businesses will have to strategically pivot their existing models and add a focus on their digital supply chain.

As a result, in order to develop comprehensive sustainment solutions, engineering innovations must be coupled with a consideration of public policy and business challenges. Only then can the full potential of the emerging technologies for the sustainment of complex critical systems be achieved.

12.4 The Economics of Sustainment

Traditionally, for many systems, sustainment is an afterthought. Unfortunately, these systems are often too expensive to replace except under emergency or catastrophic circumstances, and in many cases, the financial resources expended to sustain them over their long lifetimes effectively preclude their replacement. The cost of supporting old systems is not only economic but also safety, resource consumption, and quality of life. For example, imagine a 911 system in a major city that used the latest communications technology (instead of 15-year-old technology)—lives would be saved [30]; or FAA air traffic control systems incorporating the latest technology (rather than 25-year-old technology)—aircraft could fly with reduced separation and more optimal paths, significantly improving efficiency [31, 32]. These systems are too expensive to replace or even update, and therefore they become costly legacy systems that eventually impact people's lives (convenience and most importantly safety).

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[3] The DoD's military departments own and operate industrial facilities to maintain, repair, and overhaul equipment that are referred to as organic depots.

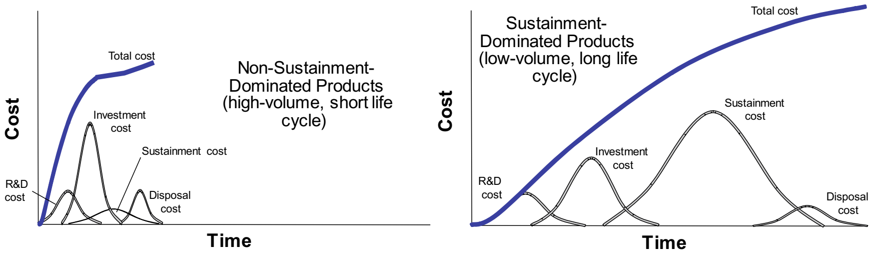

Fig. 12.1 Life-cycle spending profile for high and low volume products, [19]

A sustainment-dominated system is defined as a system for which the life-cycle footprint significantly exceeds the footprint associated with making it [7]. Sustainment-dominated systems are generally manufactured and supported for very long times, are very expensive to replace, and have very large qualification/certification overheads. Figure 12.1 illustrates the difference between sustainment-dominated products and non-sustainment-dominated products. Non-sustainment-dominated products are generally high-volume products sold to the general public that have relatively little investment in sustainment activities (probably only a limited warranty) and the total life cycle of the product (production and support) is short (e.g., a particular model of cell phone). Alternatively, sustainment-dominated products, are low-volume expensive systems, have large sustainment costs and long manufacturing and/or field lives (e.g., an airplane).

Commercial companies that develop critical systems consider operating and support costs integral to their product development decisions. Controlling these costs directly impacts revenues, profits, and market growth. Consequently, they establish product availability, operating, and sustainment costs as key system requirements. As a result, the product developers focus on designing a product that meets the availability requirements, is easy to maintain, and reliable. When we look at government system development, although they may have the same vision, their execution is often flawed. The US DoD's systems often last decades, and their sustainment dominates life-cycle costs (LCC), typically 60–80% of LCC for a system that lasts 30 years [33]. However, when faced with immediate near-term pressures, such as those related to R&D, production, and system acquisition costs, they must make real-time trade-offs against the future impacts those decisions may have on sustainment cost and performance 10, 20, even 30 or more years in the future. While simply understanding these trade-offs can be difficult, justifying and defending a 30–40-year return on investment against the immediate resource demands of today is even more challenging. As a result, addressing sustainment issues is often delayed, until the systems are operational, which is too late.

The value of process, equipment, and yield changes for manufacturing systems are often quantified as cost *savings*. However, the value of sustainment activities is usually characterized as cost *avoidance*. "Cost avoidance is a reduction in costs that have to be paid in the future to sustain a system" [19]. The sustainment community prefers the use of cost avoidance rather than cost savings, because an action characterized as a cost savings implies that there is money to be recovered. In the case of sustainment activities, there is no money to recover. Making business cases based on a future cost avoidance argument is challenging. Therefore, in order to make business cases to create and retain budgets for sustainment; and to support spending on strategic sustainment initiatives, it becomes of the utmost importance to understand the costs associated with sustainment (and the lack thereof).[4] In this section, we discuss estimating the costs of various attributes of system sustainment.

12.4.1 Maintenance Management

Maintenance refers to the measures taken to keep a product in operable condition or to repair it to an operable condition [35]. No one knows how much economies spend on maintenance, partly because most maintenance is performed in-house, not purchased on the market. The best numbers are collected by Canada, where firms spent 3.3% of GDP on repairs in 2016, more than twice as much as the country spends on research and development [36]. “Maintenance lacks the glamour of innovation. It is mostly noticed in its absence.” [36].

Fundamentally, maintenance is about money and time. The decision to spend money doing maintenance is based on the value obtained, i.e., money does not have to be spent on maintenance; the system could be simply discarded each time it fails and replaced with a new system. Optimizing the maintenance activities is justified by a combination of economic and availability arguments.

12.4.1.1 Corrective Maintenance

Corrective maintenance (also called “break-fix” or “run-to-failure”) primarily depends on the system’s reliability. The cost of maintenance in this case is simply the number of system failures that have to be resolved multiplied by the cost of resolving them. Assume that we have a system whose failure rate is constant. The reliability of the system is given by Eq. (12.1) as,

$$R(t) = \mathrm{e}^{-\lambda t} \tag{12.1}$$

where t is time and λ is the failure rate. The mean time between failure (MTBF) for this system is $1/\lambda$. Suppose, for simplicity, the failures of this system are resolved

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[4] Sometimes this is referred to as “life-cycle sustainment planning” [34]. The purpose of life-cycle sustainment planning is to maximize readiness by delivering the best possible support outcomes at the lowest Operating and Support (O&S) cost. Programs that emphasize sustainment early in the system life cycle, deliver designs with the highest likelihood of achieving operational performance requirements, and reduced demand for sustainment.

instantaneously at a maintenance cost of \$1000/failure. If we wish to support the system for 20 years and the units on λ are failures/year, how much will it cost? Assuming that the discount rate on money is zero, this is a trivial calculation:

$$\text{Total Cost} = 1000(20\lambda) \tag{12.2}$$

The term in parentheses is the total number of failures in 20 years. If $\lambda = 2$ failures per year, the Total Cos*t* is \$40,000. If we include a cost of money, i.e., a discretely compounded discount rate (r), the solution becomes a sum, because each maintenance event has a different cost in year 0 dollar,

$$\text{Total Cost} = \sum_{i=1}^{20\lambda} \frac{1000}{(1+r)^{i/2}} \tag{12.3}$$

where $i/2$ is the event date in years.[5] If we assume $r = 8\%$/year, the Total Cost is now \$20,021.47 in year 0 dollar.

In reality, the actual event dates in the example presented above are not known (they do not happen at exactly MTBF intervals), rather the time-to-failures are represented by a failure distribution. The failure distribution can be sampled to capture a sequence of failure events whose costs can be summed using Eq. (12.3). See Ref. [19] for an example.

In the simple example described, 20λ in Eq. (12.2) is the number of "spares" needed to support the system for 20 years (if $\lambda = 2$ failures/year then 40 spares are necessary). Sparing analysis, i.e., determining the number of spares required to support a system for a specified period of time to a specified confidence level is central to maintenance planning and budgeting. In general, the number of spares needed can be determined from Ref. [37],

$$\Pr(X \le k) = \sum_{x=0}^{k} \frac{(n\lambda t)^x e^{-n\lambda t}}{x!} \tag{12.4}$$

where

k = number of spares.
n = number of unduplicated (in series, not redundant) units in service.
λ = mean failure rate of the unit or the average number of maintenance events expected to occur in time t.
t = time interval.
$\Pr(X \le k)$ = probability that k is enough spares or the probability that a spare will be available when needed (this is known as the "protection level" or "probability of sufficiency").

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[5] The $i/2$ assumes that $\lambda = 2$ and the failures are uniformly distributed throughout the year.

Solving Eq. (12.4) for k gives the number of spares needed. The time interval (t) in Eq. (12.4) can be interpreted several ways. If the spares are permanent than t is the total time that the system needs to be supported. Conversely, if the spares are only required to support the system while the original failed item is being repaired, then t is the time-to-repair the original item.

Renewal functions are another way of estimating spares. A renewal function gives the expected number of failures in an interval. For a constant failure rate, the number of renewals in a period of length t is given by,

$$M(t) = \lambda t \tag{12.5}$$

For other types of time-to-failure distributions (e.g., Weibull), the renewal function may not have a simple closed-form like Eq. (12.5) but can be estimated using,

$$M(t) = \frac{t}{\mu} + \frac{\sigma^2}{2\mu^2} - \frac{1}{2} \tag{12.6}$$

where μ is the mean and σ^2 is the variance of the distribution (this estimation is valid for large t, other approximations exist). For a three-parameter Weibull distribution, the μ and σ^2 are given by,

$$\mu = \gamma + (\eta - \gamma)\Gamma\left(1 + \frac{1}{\beta}\right), \sigma^2 = (\eta - \gamma)^2\left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma^2\left(1 + \frac{1}{\beta}\right)\right] \tag{12.7}$$

where β is the shape parameter, η is the scale parameter, and γ is the location parameter.

$M(t)$ and k are not the same thing. k is the number of spares necessary to satisfy a specified confidence that you have enough spares to last t (i.e., $\Pr(X \leq k)$ in Eq. (12.4)). $M(t)$ is the expected number of spares needed to last for t. Renewal functions are commonly used to estimate warranty reserve funds for a warranty period of t and to estimate maintenance budgets, but if one wants to know how many spares are necessary to satisfy a particular confidence level then a treatment like that in Eq. (12.4) is necessary.

To illustrate the analysis of maintenance costs, consider a bus that is intended to operate for 200,000 miles per year. Reliability analysis indicates that the failure of a critical component follows an exponential distribution with a failure rate of $\lambda = 1.4 \times 10^{-5}$ failures/mile. Assume that it takes 5 days (2740 miles of lost bus usage) and costs \$5,000 each time the component must be replaced when it fails.[6] Assume that the replacement component is "as good as new" and that the failure mechanism

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[6] Note, everything in this illustration is in miles rather than time. Mileage can be converted to time if desired, but it is not necessary to do so. We are also assuming that all maintenance is via component replacement, i.e., there is no component repair.

only accumulates damage while the bus is operating (not while it is being repaired). What is the expected maintenance cost for one bus, for 1 year?

The component failures follow an exponential distribution, so we can use Eq. (12.5) to estimate the number of renewals in 1 year (200,000 miles) period. Using Eq. (12.5), we get $M(t = 200{,}000) = 2.8$ renewals/year (repairs in this case). This would be the correct number of repairs if the relevant failure mechanism accumulated damage continuously over calendar time, but because it only accumulates damage when it is operating, this is too large. The time (miles) to perform the corrective maintenance is not zero (the calculation above implicitly assumes it is zero, i.e., it assumes the bus is fixed instantaneously on failure, which it is not). One way to fix this is by adjusting the failure rate,

$$\lambda_{\text{modified}} = \frac{1}{{}^{1}\!/\!_{\lambda_{\text{original}}} + 2740} = 1.348 \times 10^{-5} \text{ failures/year} \tag{12.8}$$

Equation (12.8) effectively extends the MTBF ($1/\lambda_{\text{original}}$), by the maintenance duration. Using the new value of λ, $M(t = 200{,}000) = 2.697$ renewals.[7]

Now, the annual maintenance cost for a bus is given by,

$$\text{Cost}_{\text{annual}} = c_f M(t) \tag{12.9}$$

where c_f is the cost per maintenance event. For the bus problem, from Eq. (12.9) with $c_f = \$5000$, the annual maintenance cost per bus is \$13,668. The operational availability of the bus is given by,

$$\text{Availability} = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} = \frac{200{,}000 - (2.697)(2740)}{200{,}000} = 0.9631 \tag{12.10}$$

The availability is the fraction of time that the bus is operational.

How many spares do we need to have a 90% confidence that we have enough spares for one bus for 1 year? 2.697 is the expected number of spares (per bus per year). To solve this problem, we need to use Eq. (12.4) with $n = 1$ (one bus). When $k = 3$, the confidence level is $\Pr(X \le k) = 0.69$; to obtain a confidence level greater than 0.9, $k = 5$ spares have to be used, $\Pr(X \le k) = 0.93$ in this case.

12.4.1.2 Preventative Maintenance

Next, we consider preventative maintenance. Preventative maintenance potentially avoids more expensive corrective maintenance. Corrective maintenance is generally

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[7] 2.697 is the expected number of spares (per bus per year). If we want to know the corresponding confidence level, or conversely the number of spares needed to meet a given confidence level, we have to solve this problem using discrete-event simulation.

more costly because it occurs at unplanned times making the logistics of repair more difficult and it may cause collateral damage to other system components. To assess the cost of a system with a combination of corrective and preventative maintenance, we define a maintenance cycle length, which is the length of time between maintenance events (corrective or preventative). In terms of this maintenance cycle length, the total maintenance cost per unit time is given by Ref. [38],

$$\begin{aligned}\text{Cost}(t_p) &= \frac{\text{Total expected replacement cost}}{\text{Expected maintenance cycle length}} = \frac{R(t_p)c_p + [1 - R(t_p)]c_f}{R(t_p)t_p + \int_0^{t_p} tf(t)dt} \\ &= \frac{R(t_p)c_p + [1 - R(t_p)]c_f}{\int_0^{t_p} R(t)dt}\end{aligned} \tag{12.11}$$

where

t_p = preventative maintenance time.
c_p = preventative maintenance cost.
c_f = corrective (on failure) maintenance cost.
$R(t)$ = reliability at time t.
1-$R(t)$ = unreliability at time t.
$f(t)$ = PDF of the failure distribution.

The maintenance interval (t_p), is determined by minimizing value of Cost(t_p), i.e., determining the value of t_p that satisfies $\text{dCos}t(t_p)/\text{d}t_p = 0$. For the bus problem described in Sect. 12.4.1.1, Cost(t_p) is minimized when $t_p = \infty$, why? An exponential distribution is memoryless, i.e., the failure rate is constant and independent of the age of the system or whether preventative maintenance has been done. In order for preventative maintenance to make sense there must be an increasing failure rate over time, i.e., the system has to age.

To demonstrate preventative maintenance, let's change the example from Sect. 12.4.1.1. Assume that the failure of the component of interest follows a Weibull distribution with $\beta = 2$, $\eta = 74{,}000$ miles and $\gamma = 0$. Assuming just corrective maintenance, and using Eqs. (12.6) and (12.7) with the addition of 2740 miles to μ, the $M(t = 200{,}000) = 2.553$. Let's assume that a scheduled preventative replacement task that takes 1 day (550 miles of lost usage) and costs \$2050. In this case, $\text{dCost}(t_p)/\text{d}t_p = 0$ when $t_p = 65{,}500$ miles (solved numerically ignoring the time to perform maintenance). At $t_p = 65{,}500$ miles, Eq. (12.11) gives Cost(t_p) = \$0.07056/mile. Using discrete-event simulation, the average number of corrective maintenance events per year per bus is 1.976 and the average number of preventative maintenance events per year per bus is 1.498. The availability in this case, determined via the discrete-event simulation, is 0.9688.[8] The annual cost per bus is given by,

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[8] In this case, we assume that the preventative maintenance clock is reset to zero if the bus fails and has a corrective maintenance event prior to t_p. This also assumes the component of interest starts each year good-as-new.

$$\text{Cost}_{\text{annual}} = c_f(1.976) + c_p(1.498) = \$12{,}948 \tag{12.12a}$$

$$\text{Cost}_{\text{annual}} = \text{Cost}\left(t_p\right)(200,000) = \$14,111 \tag{12.12b}$$

Equations (12.12a) and (12.12b) do not result in the same cost. They do not match because the simulation (which is more accurate) accommodates incomplete maintenance cycles (for which the incomplete portion is free).[9]

12.4.1.3 Predictive Maintenance

Preventative maintenance occurs on some predetermined schedule, e.g., every 65,500 miles in the example in Sect. 12.4.1.2. Predictive maintenance occurs when the system needs maintenance based on reliability predictions, the actual condition of the system (condition-based maintenance) or the condition of the system coupled with the expected future environmental stress conditions (prognostics and health management—PHM). In the case of PHM, predictive maintenance cost modeling is based on the prediction of a remaining useful life (RUL). The RUL provides a time period prior to failure in which maintenance can be scheduled to minimize the interruption to system operation.[10]

The economics of predictive maintenance includes predicting the return-on-investment (ROI) associated with investing in predictive maintenance (it may be costly to add and support in systems); and optimizing when to act (and what action to take) when a predicted RUL (including its associated uncertainties) is obtained.

A cost avoidance ROI for PHM can be calculated using Ref. [39],

$$\text{ROI} = \frac{\text{Cost Avoided} - \text{Investment}}{\text{Investment}} = \frac{C_u - C_{\text{PHM}}}{I_{\text{PHM}}} \tag{12.13}$$

where

C_u = life-cycle cost of the system managed using unscheduled (corrective) maintenance.

C_{PHM} = the life-cycle cost of the system when managed using a PHM (predictive) maintenance approach.

I_{PHM} = the investment in PHM when the system is managed using a PHM (predictive) maintenance approach.

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[9] If the length (in miles) of the problem is increased, the two models will converge to the same cost.

[10] For example, if an airline had a 24-h RUL prediction (assume there is no uncertainty in this prediction), they could reroute an aircraft to insure that it was at an airport that has the appropriate maintenance resources between midnight and 6 am tomorrow morning to obtain the required maintenance without interrupting any flight schedules.

To illustrate an ROI analysis, consider the bus example from the previous two sections. As part of the business case for the inclusion of PHM into a particular subsystem in the bus, its ROI has to be assessed. Assume the following:

- The system will fail three times per year
- Without PHM, all three failures will result in unscheduled maintenance actions
- With PHM, two out of the three failures per year can be converted from unscheduled corrective to scheduled maintenance actions (the third will still result in an unscheduled maintenance action)
- The cost of an unscheduled maintenance action is \$5000 and takes 5 days of downtime
- The cost of a preventative maintenance action is \$1000 (all repairs, no spares) and takes half a day of downtime
- The recurring cost (per system instance) of putting PHM into the system is \$20,000
- In addition, you have to pay \$2000 per year (per system instance) to maintain the infrastructure necessary to support the PHM in the system
- The bus has to be supported for 25 years.

We wish to calculate the ROI of the investment in PHM relative to performing all unscheduled maintenance. First, consider a case where the discount rate is 0. The analysis is simple in this case,

$$C_u = (25)(3)(\$5000) = \$375{,}000.$$

$$C_{\text{PHM}} = (25)[(1)(\$5000) + (2)(\$1000)] = \$175{,}000.$$

$$I_{\text{PHM}} = \$20{,}000 + (25)(\$2000) = \$70{,}000.$$

$$\text{ROI} = \frac{375{,}000 - 175{,}000}{70{,}000} = 2.86$$

If the discount rate is nonzero, the calculation becomes more involved; for a 5%/year discount rate the solution becomes,[11]

$$C_u = \sum_{i=1}^{25} \frac{(3)\big(\$5000\big)}{(1+0.05)^i} = (3)\big(\$5000\big)\frac{(1+0.05)^{25}-1}{(0.05)(1+0.05)^{25}} = \$211{,}409$$

$$C_{\text{PHM}} = \sum_{i=1}^{25} \frac{(1)\big(\$5000\big) + (2)\big(\$1000\big)}{(1+0.05)^i} = \$98{,}658$$

$$I_{\text{PHM}} = \$20{,}000 + \sum_{i=1}^{25} \frac{\$2000}{(1+0.05)^i} = \$48{,}188$$

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[11] There are several implicit assumptions in this analysis including that all charges for maintenance occur at the end of the year (end-of-year convention), that the \$20,000 investment in PHM occurs at the beginning of year 1, and discrete annual compounding. In this case, the values of C_u and C_{PHM} are both year 0 present values.

$$\mathrm{ROI} = \frac{211{,}409 - 98{,}658}{48{,}188} = 2.34$$

In reality, the ROI calculation associated with adding health management to a system is more complex than the simple analysis provided above. For example, predictive maintenance (e.g., PHM), will result in a combination of repairs and replacements with spares. Since the health management system will tell the maintainer to take action prior to the actual failure, some remaining life in the original component will be disposed of, which could eventually translate into the need for more spares. The availability of the system may also be a relevant issue; a simple availability calculation for this case is:

$$A_{\mathrm{no\,PHM}} = \frac{(24)(7)(365) - (3)(5)(24)}{(24)(7)(365)} = 0.9941,$$
$$A_{\mathrm{PHM}} = \frac{(24)(7)(365) - [(1)(5)(24) + (2)(0.5)(24)]}{(24)(7)(365)} = 0.9977$$

A positive or negative ROI does not make or break a business case, but, being able to assess an ROI is part of making a business case to management or to a customer.

When predictive maintenance is analyzed, the operative question is often when to perform maintenance in response to a predicted RUL. The longer the predicted RUL, the more flexibility the sustainer has to manage the system, but RULs are uncertain and the longer one waits after an RUL indication, the higher the risk of the system failing before the appropriate maintenance resources are available. One method of optimizing the action to take (and when to take it) based on an uncertain RUL is using a maintenance option.

A maintenance option is a real option is defined by Ref. [40] as,

- Buying the option = paying to add PHM to the system (including the infrastructure to support it)
- Exercising the option = performing predictive maintenance prior to system failure after an RUL indication
- Exercise price = predictive maintenance cost
- Letting the option expire = do nothing and run the system to failure then perform corrective maintenance.

The value from exercising the option is the cost avoidance (corrective vs. predictive maintenance) tempered with the potential loss of unused life in system components that were removed prior to failure or the predictive maintenance revenue loss. The predictive maintenance revenue loss is relevant to systems where uptime is correlated to revenue received (e.g., energy generation systems) and is the difference between the cumulative revenue that could be earned by waiting until the end of the RUL to do maintenance versus performing the predictive maintenance at some point that is earlier than the end of the RUL. In summary, the loss that appears in the value calculation is the portion of the system's RUL that is thrown away when predictive maintenance is done prior to the end of the RUL. See Refs. [40, 41] for the analysis of systems with maintenance options.

12.4.2 The Aging Supply Chain

Technology evolution is often driven by high-volume consumer product demands (e.g., cell phones, tablet computers, etc.), not by the type of critical systems defined in Sect. 12.3 (e.g., airplanes, control systems, networks, and power plants). As a result, unless the application is the demand driver it likely lags state-of-the-art technology by 10 or more years. Unfortunately, many of the most affected systems are safety, mission, and/or infrastructure critical so changes cannot be made to hardware or software without very expensive qualification and certification.

For sustainment-dominated systems, an aging supply chain that is not controlled by the application is reality. If we could forecast, plan for, and optimize how we manage aging technology (i.e., "gracefully" age critical systems), billions of dollars could be saved and the public's safety and convenience significantly enhanced.

The aging supply chain often manifests itself as an inability to procure the needed resources to sustain a system because the supply chain has "moved on". Most often those resources are spare parts, however, they can also be human resources (see Sect. 12.3.3), consumable materials needed to support a manufacturing process, equipment needed to manufacturing or test systems, intellectual property rights, and governance.

12.4.2.1 Diminishing Manufacturing Sources and Material Shortages (DMSMS)

DMSMS is defined as the "loss of impending loss of original manufacturers of items or suppliers of items or raw materials" [42], i.e. obsolescence. While there are several types of obsolescence, the most prevalent and relevant form for aging supply chains is procurement obsolescence, i.e., due to the length of the system's manufacturing and support life and possible unforeseen life extensions to the support of the system, the necessary components and other resources become unavailable (or at least unavailable from their original manufacturer) before the system's demand for them is exhausted. For many critical systems, simply replacing obsolete components with newer components is not a viable solution because of high reengineering costs and the potentially prohibitive cost of system requalification and recertification. For example, if an electronic component in the 25-year-old control system of a nuclear power plant fails, an instance of the original component may have to be used to replace it because replacement with a component that has the same form, fit, function and interface that is not an instance of the original component could jeopardize the "grandfathered" certification of the plant.

Electronic components are the most impacted and most managed aging supply chain components. A host of obsolescence mitigation approaches are used ranging from substitute/alternate parts to aftermarket suppliers and emulation foundries. A common mitigation approach is called lifetime buy. Lifetime buys,[12] although simple in concept, can be challenging to optimize and execute. A lifetime buy means making a one-time purchase of all the components that you think you will need forever. The opportunity to make a lifetime buy is usually offered by manufacturers of electronic components prior to part discontinuance (in the form of a published "last order date"). Lifetime and bridge buys play a role in nearly every component obsolescence management portfolio no matter what other reactive, proactive, or strategic management plans are being followed. At its most basic level, a lifetime buy means simply adding up all the projected future demand for the component, adding some "buffer" to that quantity, and buying and storing those components until needed. Unfortunately, everything is uncertain (most notably the demand forecasts) and the cost penalties for buying too few components can be astronomically larger than the penalty for buy too many components.

In this chapter, we not only present a simple lifetime buy quantity optimization treatment but also warn the reader that real lifetime buy optimization is done via stochastic discrete-event simulation for a number of reasons that will be articulated later in this section. The lifetime buy optimization problem is a version of the Newsvendor Problem (a classic optimization problem from operations research). The newsvendor problem seeks the optimal inventory level for an asset, given an uncertain demand and unequal costs for overstock and understock. In Newsvendor problems, the critical ratio is

$$F\left(Q_{\text{opt}}\right) = \frac{C_U}{C_O + C_U} \tag{12.14}$$

The factors relevant to solving this problem are:

$F(Q)$ the cumulative distribution function (CDF) of demand evaluated for a particular lifetime buy quantity of Q.

C_O the overstock cost—the effective cost of ordering one more unit than what you would have ordered if you knew the exact demand (i.e., the effective cost of one left-over unit that cannot be used or sold).

C_U the understock cost—the effective cost of ordering one fewer unit than what you would have ordered if you knew the exact demand (i.e., the penalty associated with having one less unit than you need or the loss of one sale you can not make).

Q the quantity ordered.

D demand.

The objective is to find the value of Q that satisfies Eq. (12.14), i.e., Q_{opt}.

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[12] Also called life-of-need, life-of-type, or all-time buys. Alternatively, bridge buys mean purchasing enough parts to last until a planned design refresh point in the future where the part will be designed out.

Consider the bus example, we defined in earlier sections of this chapter. Assume that there will be no future opportunity to procure additional spare parts for the component, we previously considered (with an exponential distribution with $\lambda = 1.4 \times 10^{-5}$ failures/mile). A lifetime buy is offered for this component. How many spare components should be bought per bus now to support 10 years worth of bus operation? Assume that the components cost \$1400 to procure now, but if you run out of components and have to procure them from a third party in the future, they will cost \$20,000 per component. Using Eq. (12.14) with $C_U = \$20{,}000 - \$1400 = \$18{,}600$, and $C_O = \$1400$, $F(Q_{\text{opt}}) = 0.93$. $F(Q)$ is the CDF of the demand, which means that life-cycle cost is minimized by purchasing the number of components gives you 93% confidence that you have enough spares. In the last paragraph of Sect. 12.4.1.1, this problem was worked using Eq. (12.4) and the number of spares that satisfied a 93% confidence was found to be 5 spares/year, therefore $Q_{\text{opt}} = 5$, which indicates that you will need (5)(10) = 50 components/bus purchased at the lifetime buy to last 10 years. Note, the actual demand is 2.697 spares/year, Q_{opt} is larger because of the asymmetry in the penalties, for example, if the future cost was \$4500, then the $F(Q_{\text{opt}}) = 0.69$, which corresponds to 3 spares/year.

The treatment of lifetime buy quantity optimization using a Newsvendor approach is elegant, but does not incorporate several key attributes of the problem, most notably Newsvendor solutions do not accommodate time. Time enters into the problem as discounting of the cash flows and in holding costs. The initial purchase of parts happens at time zero and does not need to be discounted, however, the penalties C_O and C_U occur years later when the buy runs out or the support of the system ends. C_O and C_U can be discounted and if one assumes that they would occur at approximately the same future time, then the value of $F(Q_{\text{opt}})$ given by Eq. (12.14) is unaffected. The bigger problem is holding cost.[13] Holding happens continuously until parts are used up—this is a problem that we cannot overcome with the newsvendor solution, and holding costs are not negligible.[14] See Ref. [43] for a more extensive treatment of lifetime buy problems.

Lifetime buys are a common reactive mitigation approach to obsolescence management. Because of the long manufacturing and field lives associated with sustainment-dominated systems, they are usually refreshed or redesigned one or more times during their lives to update functionality and manage obsolescence. Unlike high-volume commercial products in which redesign is driven by improvements in manufacturing, equipment or technology, for sustainment-dominated systems, design refresh is often driven by technology obsolescence that would otherwise render the product unproducible and/or unsustainable. The challenge is to determine the optimum design refresh plan (dates and content) that balances reactive obsolescence mitigation (including lifetime buys) with the large expense of redesign and

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[13] There are Newsvendor solutions that include holding costs, however, the holding costs are \$/part (no time involved), so these types of holding costs are not applicable to the lifetime buy problem.

[14] For parts that have to be stored for many years in environmentally controlled inventory facilities, it is not unusual for the holding cost of the parts to be many times larger than the original cost to procure the parts.

requalification. The refresh planning problem can be articulated as finding the Y_R that minimizes, (12.15)

$$C_{Total} = \underbrace{\sum_{i=1}^{N} C_{before_i}}_{\text{Buying components as needed from 0 to their obsolescence date}} + \underbrace{\sum_{i=1}^{N} C_{LTB_i}}_{\text{Lifetime buy of components at their obsolescence date}} + \underbrace{\sum_{i=1}^{N} C_{H_i}}_{\text{Lifetime buy holding cost}} + \underbrace{C_{DR}}_{\text{Design refresh cost (all obsolete components addressed)}} + \underbrace{\sum_{i=1}^{N} C_{after_i}}_{\text{Buying components as needed from } Y_R \text{ to } Y_{EOS}} \tag{12.15}$$

where C are discounted costs, there are N total unique components, with a single design refresh at Y_R. The simplest solution to Eq. (12.15) only includes the second and fourth terms (the component buy to get to the refresh and the refresh costs) for a single ($N = 1$) component is known as a Porter model [44] for which closed-form solutions to this exist [19].

More detailed solutions to Eq. (12.15) exist including discrete-event simulation models that can find multiple refresh optimums and include other reactive mitigation options besides just last-time buys, e.g., Ref. [45]. These solutions can also incorporate various constraints governing when refreshes can and cannot occur [46].

12.4.2.2 Counterfeit Components

The obsolescence of components creates an opportunity for counterfeit components [47]. Counterfeit components are components that are misrepresented to the customer and may have inferior specifications and quality. Counterfeit components can take many forms, they may be used (salvaged) components misrepresented as new, remarked components, manufacturing rejects, components manufactured during factory shutdowns, and others. Whatever the form of the counterfeit, these components are problematic in critical systems. The risk of obtaining counterfeit components increases substantially when components become obsolete and have to be procured from sources that are not the original manufacturer.

12.4.2.3 Sourcing Small Quantities

For lean manufacturing approaches used for high-volume products (e.g., hundreds of thousands to millions of products a year), supply-chain disruptions are usually relatively short in duration (e.g., hours or days). For critical systems that are low volume (e.g., hundreds to a few thousand products a year) manufactured and supported for long periods of time, supply-chain disruptions may have durations of months or even years. Unlike high-volume products, critical systems often do not focus on minimizing the procurement prices of the components, rather, they care more about supply-chain stability because they are often subject to system availability requirements that penalize them if the product does not operate due to a lack of spare components.

High-volume applications commonly use a host of approaches to minimize their sourcing risk including second sourcing, and other strategies. This sourcing strategy decreases the impact of disruptions as component orders can be rerouted to the other suppliers when disruptions occur. For high-volume demand, multisourcing strategies are good for supplier negotiations (manufacturers can put pressure on the price), but for low-volume demand there is often little or no supplier negotiation. For low-volume demand,[15] the additional qualification and support costs associated with a backup source can negate its benefits. Single sourcing is defined as an exclusive relationship between an original equipment manufacturer (OEM) and a single supplier with respect to a specific part. However, while single sourcing minimizes qualification costs and allows for greater supplier–manufacturer coordination, the manufacturer is more susceptible to supplier-specific disruptions.

Buffering involves stocking enough parts in inventory to satisfy the forecasted component demand (for both manufacturing and maintenance requirements) for a fixed future time period so as to offset the impact of disruptions. While buffering can decrease the penalty costs associated with disruption events, there can be negative impacts, e.g., it can delay the discovery of counterfeit components in the inventory. Similarly, long-term storage of components can lead to part deterioration (such as the reduction of important solderability characteristics for electronic parts). For this reason, OEMs that utilize long-term buffering as a disruption mitigation strategy need to employ unique (and potentially expensive) long-term storage techniques that include regular assessment of the status/condition of the buffered components.

The supply chain for critical systems can also be subject to allocation problems. Allocation issues can occur for components that are not obsolete, but have extremely long delivery times (e.g., months to years). This is often due to circumstances that are out of the control of the system sustainers (natural disasters, political unrest, pandemics, etc.) that limit the quantity of components available on the market. When demand significantly exceeds supply, usually the largest customers (e.g., highest-volume customers) are supplied before low-volume customers meaning that critical systems may go to the "back of the line" for their components.[16]

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[15] As additive manufacturing technologies and processes mature, they will create an alternative path for the production of some low-volume components.

[16] Note, some critical systems, i.e., approved national defense and energy programs may be covered by the Defense Production Act (DPA) and thereby can be given allocation priority. With respect to technology, the DPA was invoked by President Donald Trump for critical technology in the space industry [48] and more recently associated with ventilator manufacturing to combat the COVID-19 pandemic.

12.5 The Role of Policy and Acquisition in Sustainment

The sustainment of complex systems across the span of their life cycle involves a range of planning, implementation, and execution activities. These systems must meet user needs, as evidenced by their availability, effectiveness, and affordability. To achieve the best results, requires that sustainment be considered during all phases of the system's life cycle, particularly during the initial phases of its acquisition. Sustainment professionals need to be involved early in the system's development to influence the system design and support concepts for sustainability, since decisions made early in a program's development will have a profound impact on the system's life-cycle cost.

During these early phases, when examining performance requirements trade-offs (e.g., speed, range, payload), they should be balanced with the system sustainment requirements (e.g., availability, reliability, operating and support costs). These decisions should be based on a business case analysis to identify and compare the various alternatives, then analyze the mission and business impacts, risks, and sensitivities.

Technological trends are also placing increasing emphasis on digital data to support sustainment applications, such as prognostic health monitoring, condition-based maintenance, additive manufacturing, and failure prediction. Consequently, early in the life of programs, acquisition decisions must be made regarding the data collection and data rights.

12.5.1 A Broadened Sustainment Perspective

The concept of sustainability implies that a stakeholder's present needs are met while not placing the future well-being of the stakeholders at risk.

Under the best of circumstances, sustainment provides a framework for assuring the financial, security, and mission-success of an enterprise (where the enterprise could be a population, company, region, or nation). However, today, sustainment is usually only recognized as an organizational goal after it has already impacted the bottom line and/or the mission success of the organization, which is too late. Given that increasingly complex systems are embedded in everything, the sustainment culture needs to change to make it a part of the system's design and planning. Suggestions include [1]:

(1) Design systems for sustainability from the beginning of the system's development.
(2) Developing sustainment requirements and metrics is as critical to a program's success as identifying requirements for cost, schedule, and performance; but, often does not receive the requisite attention.
(3) Socialize the concept of sustainment. Generally, universities are good at preparing students to design new things, but the majority of students receive

minimal exposure to the challenges of keeping systems going or the role that government policies play in regulating sustainment.

- We need to educate students (engineers, public policy, and business) to contribute to the sustainment workforce.
- We need to educate everyone—even the students that will not enter the sustainment workforce need to understand sustainment because all of them will become customers or stakeholders at some level (taxpayers, policy influencers, decision-makers, etc.). The public has to be willing to resource the sustainment of critical systems.

(4) Leverage sustainment to create more resilient systems—resilience is more than just reliable hardware and fault-tolerant software. Resilience is the intrinsic ability of a system to resist disruptions, i.e., it is the ability to provide required capability in the face of adversity, including adversity from nontechnological aging and governance issues. Resilient design seeks to manage the uncertainties that constrain current design practices. From an engineered systems point of view, system resilience requires all of the following:

- reliable hardware and fault-tolerant software;
- resilient logistics (which includes managing changes that may occur in the supply chain and the workforce);
- resilient legislation or governance (rules, laws, policy);
- a resilient contract structure;
- and a resilient business model.

(5) Sustainment is not only an engineering problem. Engineering, public policy, and business must all come together in order to appropriately balance risk aversion with innovation and system evolution.

The world is full of complex systems (communications, transportation, energy delivery, financial management, defense, etc.). Because these systems are expensive to replace, they often become "legacy" systems. At some point, the amount of money and resources being spent on sustaining the legacy system hinders the ability to invest in new systems, creating a vicious cycle in which old systems do not get replaced until they become completely unsustainable or result in a catastrophic outcome.

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