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# Measuring the Life-Cycle Value of Enduring Systems

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## ABSTRACT

A goal of systems development is to produce enduringly valuable product systems—i.e., systems that are valuable when delivered to their users and which continue to be attractive to their stakeholders over time. However, quantifying the life-cycle value (LCV) provided by a system has proven elusive. In this paper, we propose an approach to quantifying a system's LCV based on the key parameters that have perceived value to the system's stakeholders. For this, we draw upon insights from the management, marketing, product development, value engineering, and systems engineering literature. We then demonstrate our proposed approach with an example of a cellular telephone system. By designing systems for maximum LCV, systems architects and engineers will provide dramatically increased value to their organizations and other stakeholders. However, to provide maximum LCV, a system may need to be designed to facilitate adaptability to changing circumstances and stakeholder preferences. We conclude the paper with discussions of some of the major difficulties in measuring LCV and some of the opportunities for further research in this area. © 2008 Wiley Periodicals, Inc. Syst Eng 11: 187–202, 2008

Key words: product life cycle; life-cycle value; product value; stakeholder preferences; dynamic value

## 1. INTRODUCTION

A goal of systems engineering and associated endeavors is to produce enduringly valuable systems. However, efforts toward this end have been tremendously

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inconsistent. Some systems fail to provide much value from the outset (e.g., Iridium, Global Star, some Mars explorers, Edsel); others seem good at first, but then see their value curtailed (e.g., space shuttle, Macintosh computers, BetaMax VCRs); still others continue to provide high value for decades (e.g., B-52, F-16, Voyager spacecraft, Fenway Park). While many have explored value engineering in the design process [e.g., Green, 1994; Park, 1998], in this paper we focus on a much more specific topic—quantifying the life-cycle value (LCV) provided by a (product) system.

We are especially interested in what we call enduring systems—i.e., products with relatively long lifetimes. Most large, complex, and expensive systems are anticipated to have a fairly long life cycle, and even simpler systems' life cycles are extending from the perspective of the product platforms that give rise to multiple product generations.[1] LCV is becoming more important as the complexity and costs of systems increase, as the environments of system operation become more dynamic, and as designers and customers become more aware of its implications—e.g., in the trucking industry [Kilcarr, 2005]. And while many on the finance side have traditionally neglected the long-term implications of systems, under the assumption that economic discount rates will render negligible any effects beyond a decade or so, this premise does not fully apply to enduring systems, because their direct and indirect effects are likely to amplify over time [Cutcher-Gershenfeld et al., 2004]. A perspective that discounts the future (in favor of the present) is also problematic as operational environments and expectations become more volatile [Kulatilaka, 1993].

The value provided by a system, let alone its LCV, is difficult to quantify. Value is largely subjective, and individuals have difficulty articulating exactly what makes a complex system valuable. A particular stakeholder in the development or use of a complex system is typically represented by a group of individuals with conflicting opinions. Plus, there are usually a variety of stakeholders, and thus an even greater likelihood of conflicting points of view on value. Moreover, value is not only absolute—i.e., based on the intrinsic attributes, functions, and performance levels of a system—but also relative, based on perception and depending on the availability and attributes of substitute products, services, or approaches for meeting needs and wants. Finally, stakeholder needs and wants, and the perceived value of a system, change over time, thus making LCV even more amorphous. Clearly, designing for maximum LCV is not easy when even the objective itself is difficult to specify.

System architects and designers should be familiar by now with the need to listen to the "voice of the customer" and other stakeholders when determining system requirements. However, systems designers should keep the overall LCV in mind, not just what will satisfy stakeholders today. The selection and design of an "intervention system" [Martin, 2004] (also known as a "solution system") is the time of highest leverage for affecting its LCV, for here system architects and designers will make decisions (deliberately or not) that predetermine much of a system's flexibility, adaptability, upgradeability, etc. Choices about product platforms, standard interfaces, modularity, capacity, and other aspects of system architecture will enable a system to be modified, enhanced, expanded, and upgraded more or less quickly, cheaply, and easily in the future. Of course, such decisions must also be balanced against the preferences of stakeholders in the financial realm, who may differ in their attitudes towards risk and their preferences for short-term or long-term returns. Increasing flexibility may decrease the short-term profitability of a system.

Despite system designers' (often underutilized) capability to design for LCV, this is only one side of the coin. While the designers control a system's absolute attributes, LCV is a relative thing, determined also by alternative solutions to evolving stakeholder needs and wants. The perfect desktop computer today may quickly become obsolete as new technologies and designs alter customer perceptions about what is the "best" or a "satisfactory" product, or a high-value system may require replacement parts that at some point become difficult to get (from "diminishing sources"), driving up the costs of maintenance and thereby lowering its value in the eyes of its users. Over time, stakeholders also learn more about their needs and wants in light of the current solution and develop a greater perception of the possibilities for a better solution. All else being equal, a gap grows over time between the user's wants and needs and the capabilities of a system to satisfy them.

Therefore, designers must consider not only how to meet specifications that will satisfy stakeholders today but also the trajectories of markets and technologies that will determine what it takes to satisfy stakeholders in the future. How are stakeholder wants and needs evolving? What new technologies are likely to increase their

[1] It is important to distinguish our use of the term "life cycle" from its usage in the marketing literature [e.g., Bayus, 1998], where the consumer product life cycle or lifetime is usually defined as the time from a product's introduction until its withdrawal from sale (without regard for how long each individual product may persist in use). The classic Bass [1969] model of product diffusion into a market similarly looks at the life cycle of a consumer product in terms of its adoption by customers, whereas we are more concerned with the usage lifetime of a single product instance.

expectations? What competing or substitute products or technologies will vie for their attention? Carefully forecasting answers to these questions, and systematically updating and improving these predictions as more information becomes available, is an essential aspect of designing for maximum LCV.

This paper contributes a conceptual exploration of some of the key ideas surrounding LCV and the genesis of a proposed approach for quantifying a system's LCV. After reviewing related literature, we present the key steps and parameters for quantifying LCV along with a running example. We then discuss some further uses of the approach, its dynamic aspects, and some of its uncertainties and risks, all of which point to opportunities for further research.

## 2. RELATED LITERATURE

Much research has been done on the subject of quantifying value during the design process, but much less research has explored the subject of LCV. In this section, we provide an overview of some of the related literature.

A thread of thinking on system operational and disposal costs (i.e., post-production costs) runs through several streams of literature, such as military logistics and maintenance [LOGTECH, 2002]. Most of these sources argue for additional thought and effort to be put into addressing these issues and minimizing these costs at the point of greatest leverage, during the system design phase. As systems engineers, this is where we focus.

A recent project at Loughborough University, Value in Design (VALiD)[2] explored how stakeholders articulate their preferences and how designers respond to them in the building construction industry in the United Kingdom. As part of this stream, Devine-Wright, Thomson, and Austin [2003] address the psychological aspects of how people place value on a building and its architecture, and Thomson et al. [2003a, 2003b] strive to show that there is more to value than functional interpretations and measurements. The VALiD approach is inspired in part by Thiry [2001], who promotes a "sensemaking" approach to value definition in projects, whereby all stakeholders' preferences are elicited in a new, shared paradigm instead of within their own, old, individual paradigms. In the German building construction industry, Bogenstätter [2000] discusses how buildings can be designed for sustainability and lower recurring costs over their lifetimes through design decisions regarding space, material choices, service equipment, and the quantity of structural elements.

Cook and his colleagues [e.g., Cook and Wu, 2001; Cook, 1997] explore methods for quantifying the value of a system during the design phase. For instance, Pozar and Cook [1998] demonstrate how to measure the relative value of an automobile design as a function of one of its attributes (vehicle interior noise). Fitch and Cooper [2005a, 2005b] review several approaches to modeling and analyzing product life-cycle value—many of which pertain to design for sustainability and environmental impact—and propose methods for evaluating alternative design scenarios.

From a systems engineering (SE) viewpoint, Gilb [2004] discusses how to account for stakeholder desires in project planning, and Warmkessel and Slack [1999] discuss doing so during requirements development. Honour [2001, 2004] and Ring [2000] explore the value of SE and "how much" SE is appropriate for a project. Larsen and Buede [2000] propose continuous, early validation to ensure the correct capture of stakeholder wants and needs. Fabrycky, Blanchard, and Verma [1999] and Redman and Crepea [2006] suggest basic constructs for life-cycle cost modeling and propose that life-cycle cost be considered as an explicit factor in system design trade studies. Steiner [1998] discusses "enduring," "growth," and "evolutionary" architectures, and Schulz, Fricke, and Igenbergs [2000] define several concepts pertaining to design for flexibility and adaptability over the life cycle of a system. Boas and Crawley [2007] coined the term "divergence" for the natural reduction of commonality over time due to requirements changes, learning, the availability of new technologies, obsolescence, program timing, and corporate culture. de Weck and colleagues provide several papers with examples of systems designed for flexibility [e.g., Banerjee and de Weck, 2004; Silver and de Weck, 2007; de Weck, Neufville, and Chaize, 2004; Kalligeros and de Weck, 2004; Kalligeros, 2004; Suh et al., 2007]. Some of these works, as well as work by Nilchiani, Hastings, and Joppin [2005] and Wang [2005], seek ways to measure flexibility in system designs with options-based frameworks. Engel and Browning [2008] propose an options-based method for designing system architectures for adaptability.

In the US defense-aerospace industry, Murman et al. [2002] and Stanke [2001] use case studies of enduringly valuable systems such as the F-16 aircraft to explore the application of Lean principles as they affect the favorable conditions for high LCV. They offer insights and a framework for increasing LCV during the design phase. Rebentisch et al. [2005] examine 13 stakeholder groups in NASA's space exploration program with a view towards the sustainability of that program over time.

[2]www.valueindesign.com

Cutcher-Gershenfeld et al. [2004] explore the benefits of designing for sustainability in large-scale engineering systems and public policies, noting the need for broader information acquisition and review to permit earlier detection of side effects, independent reassessment of strategies, and analysis of retrospective examples of successful and unsuccessful business and government adaptations.

Considering how value is added by system development processes, especially in light of the Lean principle of minimizing non-value-adding activities, Browning [2003] explores how to quantify the value provided by the system development process and how different process architectures allow value to be provided or "earned" at different rates. Rouse and Boff [2001] evaluate three dimensions of value in research and development (R&D) organizations: quality, productivity, and innovation.

Customers are the primary stakeholder, and the vast marketing literature has much to say about what customers and markets value and prefer. Mello [2002] provides guidelines for customer-centric product development. Woodruff and Gardial [1996] focus on the customer value determination process, link customer value to customer satisfaction, and define a "value hierarchy" of attributes, consequences, and desired end state(s). Consequences are the result of using a product or service (e.g., reliability, no hassle) and are hard to measure directly (they do it in terms of product or service attributes). "Desired end state" is even more nebulous (e.g., "peace of mind") and is determined in terms of consequences. They also discuss how to predict changes in customer value over time. Slywotsky [1996] notes how value evolves in terms of customers' priorities, time horizons, willingness and ability to pay, etc. and concludes that products and services should be adapted to take advantage of and minimize the risks of these changes. Furthermore, R&D organizations must create the technology options to enable subsequent exercising of these options in the process of adapting value strategies and market offerings.

Freeman [1984] invigorated a stream of management research exploring the stakeholder theory of the firm—i.e., how stakeholders are determined for enterprises and their effects on organizational strategies and objectives [e.g., Sundaram, 2004]. Many of these ideas pertain to the determination of stakeholders and their preferences for any complex system. Kochan and Rubinstein [2000] distinguish between "definitive" and "latent" (i.e., direct and indirect) stakeholders. Society is also a key stakeholder in the development of large, complex, high-value systems. Emerson [2003] discusses social value as a key component of overall business/organization value and issues surrounding its quantification. However, in reviewing stakeholder theory at this level, Rebentisch et al. [2005] conclude that "past research provides no clear-cut guidance on a process to identify and assess stakeholders and their needs" (p. 2)

We use these sources, rooted in varied disciplines, as a theoretical basis for triangulating an approach to quantify a system's LCV.

## 3. QUANTIFYING A SYSTEM'S LCV

In this section, we develop the measurement concept though discussion accompanied by a running example. The discussion provides the theoretical and practical concepts, while the example illustrates their application.

The concepts presented herein are based on measurement of the perceived value of a system in the eyes of its stakeholders. This perceived value, which changes across stakeholders and across time, can be quantified in relation to a set of key parameters (KPs). This quantification requires the following steps:

1. Identify the stakeholders.
2. Identify the system's KPs.
3. Create a holistic measure of stakeholder value.
4. Anticipate and quantify the evolution of the KPs.
5. Measure stakeholder value over time: LCV.

For the example, we use a typical high-value system that has a life cycle long enough to span several technology changes, a cellular telephone network. This system encompasses a network of cell stations that provide service to subscribers, a selection of compatible telephone units that subscribers may use, and a central billing facility that tracks usage across the network.

### 3.1. Step 1: Identify Stakeholders

The value of any system can only be measured from the viewpoint of the stakeholders for whom the system provides utility. This is true because the purpose of any system is to provide value and utility to its stakeholders; this is the essence of both the system and the definition of stakeholders. It is therefore necessary first to identify the stakeholders for a system.

A stakeholder is any individual or group with a vested interest in a system. Stakeholders are willing to act in some way to preserve their interest (hence "vested" interest). They often include those who derive some benefit from the system and/or make some sacrifice for it. The idea of stakeholders is not new, but it has recently taken on greater importance. Carroll and Buchholtz [2006] posit, "Our pluralistic society has become a special-interest society," (p. 8) and go on to state that the past two decades have seen an increase in the specialization on the part of interest groups representing all sectors of society. They further argue that these trends and the rising view of corporate accountability have given way to increased expectations, and that businesses have responded with corporate citizenship initiatives (any actions intended to portray the company as a good citizen in society), thereby solidifying the increased expectations and setting the bar at new levels. Managers need to understand the salience (power, legitimacy, and urgency) of different stakeholder groups [Mitchell, Agle, and Wood, 1997] and develop strategies for stakeholder management [Savage et al., 1991] as well as practical techniques for identifying and communicating with stakeholders [McManus, 2004].

Stakeholders and their actions may be of many forms, including:

- A purchaser who expends resources to buy the system,
- A user who operates the system,
- An activist who expends time and effort to support or thwart the system,
- A maintainer who occasionally services or repairs the system,
- An owner of an interfacing system who acts to change or preserve the interface,
- A firm that derives revenue from the sale or ongoing operation or use of the system and perhaps from periodic upgrades,
- A supplier of system components who derives revenue from ongoing maintenance and periodic upgrades, including the addition of new features,
- A provider of an alternative, competing, substitute system who acts to diminish the relative value of a system in the eyes of its purchasers and users,
- A community or society whose inhabitants are affected by the operation of the system and that may expend political capital to support or thwart the system,
- A firm that owns infrastructure required to operate the system, or
- A firm that provides complementary products or services.

Identifying the stakeholders is a conscious step in the proposed LCV measurement, but we do not propose any unique method to perform the identification. If stakeholders have been identified as part of an ongoing development process, such identification suffices for our purpose. If stakeholders have not been identified, then typical means that may be used are brainstorming, market analysis, operational analysis, workflow analysis, and supply and value chain analysis. For basic guidance we refer readers to Mitchell, Agle, and Wood [1997] and McManus [2004]. Furthermore Trainor and Parnell [2007] discuss how to use interviews, focus groups, and surveys for stakeholder analysis, and Rebentisch et al. [2005] provide an extensive case study of stakeholder identification for the US space exploration program. Stakeholders may not realize their own status as such if they are not cognizant of the benefits they receive or the sacrifices they make for the system. As stakeholders gain this awareness, they frequently self-identify over time ("come out of the woodwork"), but such self-identification may be a surprise action viewed by the development team as a risk or problem. Waiting for self-identification does not suffice for our purpose, because the proposed LCV measurement is intended to be proactive rather than reactive.

#### *3.1.1. Example: Stakeholders of the Cellular System*

For the example cellular system, stakeholders can be identified through both operational analysis and value chain analysis. (Throughout this example, we purposefully simplify the analyses so as to show the principles without extending the length of this paper. The reader should easily find additional elements of analysis that would provide more depth.)

The value chain for the cellular system derives from two primary sources: subscribers who desire telephone service and shareholders who provide cash resources. Sourcing from the subscribers, additional stakeholders in the value chain include franchise holders who sell the services. Sourcing from the stockholders, additional stakeholders include the cellular corporate management and the cellular employees.

Operational analysis might include several scenarios such as telephone operation, network maintenance, and site installation. Telephone operation involves subscribers who make and receive telephone calls, the cellular employees who track and bill usage, and the cellular management structure that hires and trains the employees. Network maintenance involves cellular employees who maintain the equipment and may involve property owners who provide access to the sites. Site installation involves cellular employees who erect and install equipment, subcontractors who perform site construction services, and area activists who may act to thwart a tower placement.

To summarize, we have identified the following stakeholders for the cellular system: subscribers, shareholders, franchise holders, corporate management, corporate employees, property owners, subcontractors, and environmental activists. We note that these are potentially categories of stakeholders rather than monolithic entities. For example, the subscribers for a cellular system have a variety of wants and needs in terms of coverage, usage time, rate plans, etc. Firms will typically segment such markets into groups of somewhat similar customers. Thus, generally, stakeholders may need to be further decomposed into smaller segments until the point where each can be seen as having a fairly similar profile of preferences. Conversely, stakeholders with similar preferences may be aggregated to simplify the analysis.

## 3.2. Step 2: Identify System KPs

Unlike most engineering parameters, value is a perceived quality stemming from subjective preferences. Stakeholder preferences are distinct and different from requirements. Requirements represent a choice made to achieve a specific level of performance and specify acceptability. A system that meets its requirements will provide different value to different stakeholders, depending on their preferences. Preferences emanate from individuals, which makes them less amenable to firm analysis. Nonetheless, preferences are relevant in SE if they express the values of those affected (or perceived to be affected) by the system designers' choices.

Measuring the value of a system therefore requires understanding and quantifying stakeholders' subjective preferences regarding key attributes of the system. Each attribute is measured by a key parameter (KP).[3] But identification and quantification of subjective preferences are not trivial matters. Unfortunately, personal preferences are not always known even to the individual who holds them. The psychology literature provides means to help identify preferences such as group discussion, brainstorming, survey instruments, ontologies, and templates. In addition, preferences related to systems may be identified through operational analysis, workflow analysis, and value chain analysis, all viewed from the viewpoint of the target stakeholder.

For our purpose, preferences are expressed in terms of a set of KPs that each matter to one or more stakeholders. The KPs are usually operational in nature, because many stakeholders are more interested in the operational results than the technical implementation. For example, maintenance cost is an operational parameter; mean time between failures (MTBF) is a technical parameter. The first might be a KP for corporate management; the second is not a KP for any of the cited stakeholders.

Two broad categories of system attributes are benefits and sacrifices.[4] Benefits are all the things the stakeholders "get" as a result of the system's development and existence. Sacrifices are the things they give up, compromise on, have to live with, are disappointed with, or have to pay for as a result of the system's development and existence. Depending on its level, a KP may provide a benefit for some stakeholders and constitute a sacrifice for others. For example, a system with a high acquisition cost may be a benefit for its supplier and a sacrifice for its customer. For a third type of stakeholder, the investor, the preferred value is a balance that achieves a greater return on investment. Note that KPs for some stakeholders include profitability and other cost measures that balance against the technical measures typically considered by systems engineers [Browning, 2003].

Determining KPs requires working closely with and actively listening to stakeholders. We have already mentioned several helpful sources of insight and guidance for working with customers [Woodruff and Gardial, 1996; Mello, 2002; Thiry, 2001]. Establishing a shared vision as a baseline reference and anchoring point, and finding and involving "lead users" [von Hippel, 1986], can be helpful practices. Campbell's [2000] discussion of metrics also provides a source of helpful thinking on potentially important KPs.

The KPs are frequently different for different stakeholders and may even conflict. In the case of our example, for instance, geographical coverage is a KP for the subscriber, while reducing the visibility of towers is a KP for the environmental activist. These parameters seem unrelated at the operational level, but obviously conflict at the technical level because towers currently must be visible to provide geographic coverage.

Once available, these KPs provide a basis for a variety of system design and analysis techniques, such as Quality Function Deployment (QFD) [e.g., Akao, 1990] and Pugh's concept selection method [Pugh, 1991], to name only a couple.

***Example: Cellular System KPs***

Identifying the KPs for the cellular system involves looking at the operation from the viewpoint of each stakeholder. The key question to ask, over and over, is: "In the eyes of this stakeholder, what would make one cellular system better than another?" Table I provides a representative list of the KPs. Note that this list has been simplified; many of the parameters shown would need much fuller definition than is evident here. Also, other KPs and stakeholders could be added to Table I, but the list suffices for the purposes of our example.

There are several items to note in Table I that highlight difficulties in this process of identifying subjective preferences. First, note the large number of different parameters. Stakeholders have highly varied prefer-

[3] KPs are often synonymous with names used in other contexts, such as dimensions of performance or quality, performance attributes, critical to customer characteristics (CTCs), key characteristics, order qualifiers and winners, etc.
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**Table I. KPs for the Example Cellular System**

| | | |
|---|---|---|
| **Subscribers**<br>• Geographic coverage<br>• System reliability<br>• Feature flexibility<br>• Usage cost<br>• Purchase cost | **Corporate Management**<br>• Return on investment<br>• System reliability<br>• Feature flexibility | **Franchise Holders**<br>• Marketability<br>• Profit |
| **Corporate Employees**<br>• System reliability<br>• Feature flexibility | **Shareholders**<br>• Return on investment | **Property Owners**<br>• Tower size (smaller)<br>• System reliability |
| **Subcontractors**<br>• Tower size (larger) | **Environmental Activists**<br>• Tower size (smaller) | |

ences for any given system. Second, we will face difficulty (but not impossibility) in quantifying many of the parameters. Because stakeholder preferences are in their own operational language (the "voice of the customer"), they are frequently not amenable to the same kind of treatment as engineering parameters. Third, the parameters are sometimes shared by several stakeholders. In this case, system reliability is important to subscribers (so that they can make their calls), corporate management (to reduce repair costs), corporate employees (to reduce maintenance workload and complaints), and property owners (to reduce the number of accesses). Last, the desired level of some parameters may be opposite for different stakeholders. Subscribers want greater geographic coverage, which requires more and larger towers. Subcontractors also want larger towers so that their work is more lucrative. Property owners and environmental activists, however, want smaller towers. These conflicting priorities are typical of most complex systems, and they must be balanced in well-considered tradeoffs.

### 3.3. Step 3: Create a Holistic Measure of Stakeholder Value

With a quantified understanding of the KPs that matter to each class of stakeholders, we can now define a holistic measure of system value to the stakeholders by combining these many KPs into a single measure.[5] There are many mathematical methods used to combine multiple parameters into a single index, but the most common is a weighted sum. Again, through surveys and interaction with the stakeholders, the relative value of each parameter to the group of stakeholders may be established. The relative weight given to each group of stakeholders is an assessment that must be made by the system owner. When the weights are combined with the predicted preference values, the result is a single measure of preferred value. If the individual parameter preferences are stated probabilistically, then the system's preferred value is a probabilistic combination of the parameters. The weights themselves can also be stochastic variables, but the combinatory procedure remains the same. A simple weighted average is only one of many possible approaches to forming a holistic measure of value. Others include geometric averaging, Analytic Hierarchy Process [Saaty, 1980], and multi-attribute utility theory [Keeney and Raiffa, 1976]. Each approach has advantages and disadvantages; all are imperfect in moving from many KP value measures to a single, holistic one. (Additional discussion is provided in Browning [1998: Chap. 7].) The weights are used to combine the actual values of the system into a single measure of system performance. This process was partially described in Honour [2001] as a quantified Objective Function for the system. In the present work, the concept is expanded to include the complexity of the KPs preferred by different stakeholders and the change in those KPs over time.

***Example: Value of the Cellular System***

For our example, we must determine numbers for the weights, the parameter preferences, and the actual system parameters. For each parameter that was identified, Table II shows the preferences (measured in terms of the indicated units). In each row, the "Worst" column represents the amount that is least preferred by that group of stakeholders, while the "Best" column represents the amount that is most preferred. The amount most likely to be acceptable is in the "Mode" column. Note that some sets of preferences operate in a positive direction (larger is better—LIB), while others operate in a negative direction (smaller is better—SIB). (Preferences can also exist for "nominal is best" KPs, where

[5]This procedure must occur in light of a well-known axiom of multivariate decision theory, that optimal decisions cannot always be made based on a vector of multiple parameters [Arrow, 1951]. Despite this difficulty, in any decision, the parameters are combined in some fashion into a single measure of value. If this combination is not performed explicitly, it is still performed implicitly by a decision-maker when choosing one option over another. The best that seems to be possible is to be aware of the general pitfalls in any approach and any specific issues in a particular case.

**Table II. Typical Analysis of System Value**

| | | Preferences | | | Value to Stakeholder Groups | | | | Total Value | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Key Parameters (KPs) (grouped by stakeholder)** | **Units** | **Worst** | **Mode** | **Best** | **Weight** | **Actual Amount** | **Norm-alized Amount** | **Weighted Value** | **Weight** | **Weighted Value** |
| **Subscribers** | | | | | | | | **0.86** | **40%** | **0.34** |
| Geographic coverage | % | 30 | 40 | 70 | 30% | 35 | 0.50 | 0.15 | | |
| System reliability | Failures/K-hrs | 10 | 5 | 0 | 10% | 7 | 0.60 | 0.06 | | |
| Feature flexibility | % | 10 | 15 | 20 | 20% | 18 | 1.60 | 0.32 | | |
| Usage cost | ¢/min | 10 | 5 | 3 | 30% | 6 | 0.80 | 0.24 | | |
| Purchase cost | $ | 150 | 40 | 0 | 10% | 50 | 0.91 | 0.09 | | |
| **Corporate management** | | | | | | | | **1.56** | **25%** | **0.39** |
| Return on investment | % | 10 | 15 | 25 | 60% | 19 | 1.40 | 0.84 | | |
| System reliability | Failures/K-hrs | 50 | 15 | 10 | 20% | 7 | 2.00 | 0.40 | | |
| Feature flexibility | % | 5 | 15 | 20 | 20% | 18 | 1.60 | 0.32 | | |
| **Franchise holders** | | | | | | | | **0.55** | **5%** | **0.03** |
| Marketability | % market share | 5 | 20 | 75 | 40% | 12 | 0.47 | 0.19 | | |
| Profit | % | 5 | 10 | 20 | 60% | 8 | 0.60 | 0.36 | | |
| **Corporate employees** | | | | | | | | **0.80** | **5%** | **0.04** |
| System reliability | Failures/K-hrs | 15 | 5 | 0 | 50% | 7 | 0.80 | 0.40 | | |
| Feature flexibility | % | 10 | 20 | 30 | 50% | 18 | 0.80 | 0.40 | | |
| **Stockholders** | | | | | | | | **1.17** | **20%** | **0.23** |
| Return on investment | % | 8 | 13 | 25 | 100% | 15 | 1.17 | 1.17 | | |
| **Property owners** | | | | | | | | **0.98** | **2%** | **0.02** |
| Tower size | Ft | 150 | 100 | 20 | 40% | 80 | 1.25 | 0.50 | | |
| System reliability | Failures/Year | 12 | 2 | 0 | 60% | 4 | 0.80 | 0.48 | | |
| **Subcontractors** | | | | | | | | **0.46** | **1%** | **0.005** |
| Tower size | Ft | 20 | 150 | 500 | 100% | 80 | 0.46 | 0.46 | | |
| **Environmental activists** | | | | | | | | **0.33** | **2%** | **0.007** |
| Tower size | Ft | 100 | 40 | 0 | 100% | 80 | 0.33 | 0.33 | | |
| **Total, all Stakeholders** | | | | | | | | | | **1.06** |

either too little or too much is not preferred.) Under "Value to Stakeholder Groups," the first "Weight" column is the relative importance of that parameter to that stakeholder group. Shown are a typical set of weights that might have resulted from an analysis of one cellular system at one point in time. (The weights are normalized to sum to 1.) The preferential weightings are followed by the actual amount of the parameter provided by the current system.

The next column shows a conversion of the actual parameter amount into a normalized amount. There are many mathematical methods that could be used to normalize the actual amount against the preferences. In this example, we chose to calculate the normalized amount from a scale that assigns 0.0 to an actual amount that matches the Min, 1.0 to an actual amount that matches the Mode, 2.0 to an actual amount that matches the Max, and that linearly interpolates amounts which fall in between. By this assignment, a normalized amount of 1.0 represents a case in which the system meets the stakeholder preferences. Normalized amounts between 0.0 and 1.0 represent cases in which the system falls short of the preferences, while numbers between 1.0 and 2.0 represent cases in which the system has added value. A more sophisticated and accurate (yet effortful) approach to mapping the KP amounts to preferences is to establish a utility function for each relationship. We actually recommend this for most cases, since the relationships are usually non-linear. (Again, additional discussion is provided in Browning [1998: Chap. 7].)

Following the normalization of the actual amount, the next column applies the weights to find the weighted value for each parameter. These are then summed to get the overall value of the system to each stakeholder group. It can be seen in Table II that this cellular system has great value to the corporate management (Value = 1.56) because it exceeds the primary preferences in all three KPs. The system has better-than-preferred value (1.17) to the shareholders. It has less-than-preferred value (0.86) to the subscribers primarily because of poor geographic coverage, and it has even poorer value to the remaining stakeholder groups.

The last two columns calculate the total value of the system, based on an appropriate set of weights that represent the relative importance of each stakeholder group (in the eyes of the system owner). The less-than-preferred value to the subscribers balances against the great value to the corporate management so that the total system value (1.06) is slightly better than preferred (by its owner). Such a measure of holistic value can be misleading, however, if the decision-maker over-weights his or her own preferences. Thus, it is important both to explore the sensitivity of overall value to the chosen weights and to prevent any single stakeholder from receiving so little value that they are likely to cause problems.

## 3.4. Step 4: Anticipate and Quantify the Evolution of KPs

In addition to knowing the identity of the KPs, measuring value in the eyes of the stakeholders also requires quantifying that preference. For each parameter, therefore, the next step is to determine the preferred amount of the KP in the eyes of the stakeholders. This preferred amount is typically discovered for commercial product systems through a process of market surveys and user group assessments.

Because preferences are subjective, they vary from individual to individual and from time to time. We model the quantified amount of a parameter as a stochastic (random) variable. As with any stochastic variable, this variable may be modeled at various levels of depth: by a single measure of central moment such as mean or median; by a series of moment descriptors such as mean, variance, and skewness; by probabilistic bounds; or by full probability distributions. One method frequently used in risk management is to relate each outcome to its relative likelihood with a triangle distribution tied to mode, minimum, and maximum, as shown in Figure 1. For an LIB parameter, the minimum amount is a pessimistic estimate and the maximum amount is an optimistic estimate. For an SIB parameter, these estimates are reversed. In any case, the mode is an estimate of the single most likely outcome for the amount of the parameter.

For our purpose of measuring LCV, however, it is insufficient to quantify the parameters at a single point in time. Stakeholder preferences change over the life cycle of a system and therefore require modeling as a time-based stochastic process. The stakeholder preferences in the past may be modeled using quantification of prior user groups; the stakeholder preferences for the future may be modeled using predictive assessments and trends, tempered with strategic judgment.

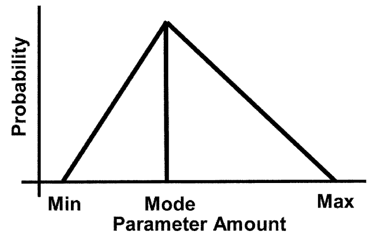


**Figure 1.** Representing a quantified parameter with a triangle distribution.

The predictive evaluation of the KPs must also take into account the possibility of new KPs, or of KPs that fade from significance.

***Example: Cellular System KP Quantification***

For our example we will demonstrate the quantification of one KP for one stakeholder: the geographic coverage in the eyes of the subscribers. For our example, we choose to quantify this parameter in terms of percent coverage. For different subscribers, however, this percent coverage means different things. We assume first, for simplicity, that the cellular system in question is restricted to the US. A US subscriber who travels extensively within the country is interested in the percent of the US covered. A subscriber whose business is within one local area is interested in percent coverage within that area. It quickly becomes apparent that quantification of this parameter requires several assumptions that translate into definition of market segments. This simple fact is why cellular companies create so many different rate plans.

The overall value of the system, however, must be determined for the total set of market segments served by the system. If this cellular system is intended to serve both countrywide and local market segments, then the percent coverage selected must be the national coverage. Through market surveys, user group assessments, subscriber entrance and exit interviews, and analysis of current subscribers' choices of "plan," perhaps the quantification of customer desires for this KP takes on the form shown in Figure 2. Note that the evolution of

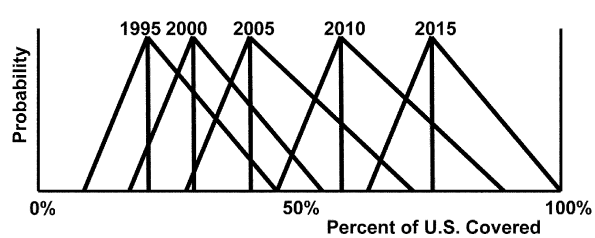


**Figure 2.** Typical predictive quantification of one KP.

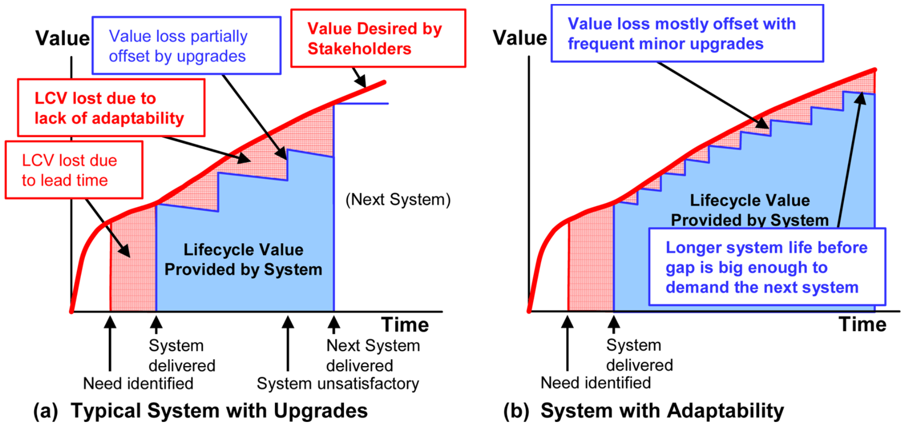


**Figure 3.** Typical behavior of LCV. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

customer desires for this KP is shown over time, with probabilistic bounds at different points in time. This quantification is showing that subscribers prior to 2015 do not expect 100% coverage, but that the desired coverage is growing over the years.

### 3.5. Step 5: Measure Stakeholder Value over Time: LCV

Now that we have developed a measure of system value in the eyes of the stakeholders, this measure can be extended to create a measure of LCV, through integrating or summing the measure over the life cycle:

$$LCV = \sum_{LifeCycleStart}^{LifeCycleEnd} TotalValue \tag{1}$$

This measure of LCV is summed rather than averaged to recognize that a system with longer life has more value to the stakeholders. As a result, the LCV can be interpreted as a count of one for each year (or other time unit) in which the system meets the preferences of the stakeholders. A system that exactly meets the stakeholder preferences (total value = 1.0) for 15 years has a LCV of 15; a system that partially meets the preferences (total value = 0.75) for 20 years also has a LCV of 15. A system that exceeds preferences for eight years and then fails to meet them for seven could also have a LCV of 15. Thus, the scalar index of LCV should not be used alone.[6]

The behavior of LCV is shown stylistically in Figure 3 for (a) a typical system with a couple of upgrades and (b) a longer-lived system built for adaptability. In the figure, the area under the curve "Value Desired by Stakeholders" represents an LCV of $Y$ (the summation of value $y_n$ over $x$ years), while the actual LCV of the system (which is less than $Y$) is indicated by the solidly shaded area ("Life-cycle Value Provided by System"). The cross-hatched regions represent the value loss as the system's capabilities vis-à-vis the stakeholders' preferences decay over time.[7] If the life of the system in Figure 3(a) is 15 years, then the proportions of the figure indicate that this system might be achieving LCV of approximately 12, while Figure 3(b) shows a similar system achieving a LCV of approximately 20, since its total value is always closer to the stakeholder preferences and its useable life is longer.

#### *Example: Cellular System LCV*

This measure of LCV, coupled with the annual measures of value, presents a method to assess the current and projected value for key management and technical decisions. Table III shows a set of historical and predicted values for two alternative cellular systems at a point in time when the corporate management is faced with hard decisions about their equipment. The existing system A has had a 10-year run of lucrative return for the company, but it is apparent that it is no longer meeting the stakeholder needs. Even with anticipated upgrades such as in 2010, the system will fall short. The more recently developed system B provides far better predicted value, but it is not yet installed over a wide geographical base. Significant capital expense will be required to change over to the new system. One advantage to the new system is its greater adaptability, seen in the fact that LCV continues to stay high in future years. As one management tool, LCV provides insight

[6]This issue could be addressed by including a discounting factor in the equation. However, the appropriate factor to use in this situation is a subject for further research.

[7]For further discussion of Figure 3 and the underlying model, see Engel and Browning [2008].

**Table III. Example LCV for Alternative Cellular Systems**

| Year | ‘98 | ‘99 | ‘00 | ‘01 | ‘02 | ‘03 | ‘04 | ‘05 | ‘06 | ‘07 | ‘08 | ‘09 | ‘10 | ‘11 | ‘12 | ‘13 | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| System A | | | | | | | | | | | | | | | | | 13.6 |
| History | .9 | 1.1 | 1.2 | 1.2 | 1.1 | 1.0 | .9 | .8 | .8 | .7 | | | | | | | 9.2 |
| Predict | | | | | | | | | | | .7 | .7 | .8 | .8 | .7 | .7 | 4.4 |
| System B | | | | | | | | | | | | | | | | | 9.9 |
| History | | | | | | | | | 1.4 | 1.3 | | | | | | | 2.7 |
| Predict | | | | | | | | | | | 1.3 | 1.2 | 1.2 | 1.1 | 1.2 | 1.2 | 7.2 |

into the value both received and expected from the system.

## 4. DISCUSSION

In this section, we discuss using the LCV measure to determine the best amount of “design for adaptability,” the dynamic nature of LCV, and risks to determining the LCV measure. This discussion illuminates opportunities for further research on the subject of quantifying LCV.

### 4.1. The “Right” Amount of Design for Adaptability

The LCV measure can provide a basis for ascertaining the value of designing a system for a certain amount of flexibility, adaptability, and sustainability. As shown in Figure 3, the system in (b) is more adaptable than the system in (a), thereby reducing the difference between customer preferences and system capabilities over time. System (b) provides greater LCV by being more easily changed when necessary to keep pace with evolving stakeholder preferences. In some cases, a system can be designed for improved adaptability with no increased cost [Bogenstätter, 2000]. However, in most cases, this capability for adaptation comes at some additional cost—e.g., the costs of:

- Designing the system around an open and modular architecture that is amenable to quick and inexpensive upgrades,
- Developing standard interfaces for the system’s modules, sometimes by participating in groups that develop and approve international and/or industry standards,
- Investing in the effort to document system design information and decisions so that future workers can easily reflect on the system’s design and build history,
- Securing multiple or contingent suppliers in case of a diminishing source issue, and
- Investing in technology and market forecasts of future system possibilities and customer preferences.

The decision about whether or not to do these things, and to what extent, depends on a benefit-cost analysis of the LCV added (to one or perhaps also other systems developed by the organization) versus the total costs. Currently, the LCV quantity is a dimensionless index, useful only for purposes of relative comparison. An absolute measure is needed to support a benefit-cost analysis. Further research is needed to convert our relative measure into an absolute one. A general approach for the conversion follows.

Incorporate forecasts of market size, market segmentation, consumer surplus, economic indicators, customer business cycle predictions, competitive system performance trajectories, and market share to determine the magnitude and direction of the evolution of stakeholder preferences and the revenue potential (monetary value) these provide. Collectively, the idea is to determine in monetary terms the benefit to the firm of keeping pace with stakeholder preferences. Since a correct forecast is not realistic, at least three benefit scenarios should be used.

Use technology roadmaps [e.g., Strauss and Radnor, 2004], material and component cost projections, operating cost projections, and information about the system architecture to determine the costs of the various upgrade sizes and frequencies needed to keep pace with stakeholder preferences. Again, because these projections are fraught with uncertainty, at least three cost scenarios should be used.

Comparing each benefit and cost scenario yields at least nine combinations. Depending on the risk sensitivity of the firm (e.g., risk averse, risk neutral, or risk seeking), a strategy can be outlined for the rough amount of resources to dedicate to design for adaptability, both in the system development process and in the system design itself.

Some initial work along these lines has sought ways to define and measure flexibility and adaptability in system designs [e.g., Saleh, Hastings, and Newman, 2003; Saleh, 2005; Nilchiani, Hastings and Joppin, 2005]. de Neufville and Scholtes [2006] suggest explicit consideration of the real options that could be purchased for potential exercise in each scenario. (See also Scholtes [2007].) McConnell [2007] introduces the concept of "complex" real options composed of interconnected technological, organizational, and process components and proposes a life-cycle flexibility framework to address issues along the entire life-cycle of an option, in both technical and social dimensions. Engel and Browning [2008] model the architecture options provided by modularity and adaptability as a tradeoff with interface costs.

It is also important to note that, when attempting to determine the appropriate amount of resources to devote to adaptability in a specific product, or on a particular development program, the common approach of phased development poses some interesting challenges. To get through the next gate or review, or to sell an idea or design for additional funding in the next phase, often requires stripping out all but the most essential product features and functions. That is, if designing a system for adaptability or maximum LCV incurs additional upstream costs, as we would typically expect, these costs may make a system design less competitive to an unenlightened customer, or to one that faces clear constraints on current but not future costs.

### 4.2. Dynamic LCV

The LCV measure is clearly an estimate made under uncertainty. Over time, as more information becomes available, this uncertainty is reduced for the near-term. Meanwhile, stakeholders expect their benefits to increase and their sacrifices to decrease. Comparators—other systems that provide benchmarks and anchor points for stakeholder perceptions—play a significant role in these rates of change. Surveys or other instruments (whatever was used initially to quantify stakeholder values as discussed above) should be repeated periodically to look for changes and trends.

The Iridium satellite telephone system cited in the Introduction is an excellent example of failure to maintain the dynamic estimates of LCV. When Iridium was envisioned in 1987, the market studies showed that it would be very successful. Potential customers were willing to pay thousands of dollars for a portable telephone that could operate anywhere in the world. The Iridium LLC joint venture launched a decade-long development program based on this marketing information. By launch of service in 1998, however, the market had seriously eroded due to the advent of cellular telephones. In the context of this paper, this failure can be described as a serious reduction in LCV due to the changing perception of the stakeholders. The service launched in 1998 was essentially the same system envisioned in 1987, with essentially the same technical parameters. The only difference was how those parameters were perceived by the stakeholders, whose subjective views had been modified by the alternative technology.

Another significant factor in LCV dynamics is customer expectations, which must be managed carefully. Interestingly, when a system is highly adaptable and upgraded frequently, customers begin to expect this, and the industry dynamics can be changed. For example, desktop computers change rapidly in terms of processor speed and other capabilities. Compared with hardware, software upgrades (of a comparable level of complexity) are relatively easy to release and are available fairly often. Anticipating a trajectory of rapid change and improvement, customers may skip some generations or releases, assuming another and possibly better one is just around the corner. Research in marketing and new product development has explored the effects of "regret," when a buyer acquires a new product only to discover shortly thereafter that it has been superseded by a more capable one. The marketing literature [e.g., Doyle and Saunders, 1985] also explores possibilities for proactively anticipating and managing customer expectations.

When their expectations are not met, customer disappointment can occur in two ways, one of which is more detrimental to a system's value. If a system developer fails to satisfy realistic customer preferences, then this is a major blow to a system's value. But customers experience another kind of disappointment when they realize that their own expectations are unrealistic. For instance, when someone discovers that no builder will build their dream house for $200,000, they are disappointed with themselves for their poor knowledge of the housing market rather than with a particular builder. However, if a particular builder has promised to build their house for $200,000 but does not meet that promise, the customer is disappointed in the builder (system developer) in a different and deeper way. Since LCV is a function of both the stakeholder preference curve and the system value curve in Figure 3, it is relatively more important to close any gap by *raising the system value curve*. However, at times it may be easier to close the gap by *lowering the "value desired by stakeholders" curve*. Traditionally, marketing organizations have addressed the latter curve while engineering organizations have tended to the former. System developers must have a firm command of both areas if they are to manage system LCV effectively, which calls for greater integration of engineering and marketing organizations.

Some aspects of future desired value may be estimated with the help of existing techniques. For example, technology roadmapping can help anticipate potential technology switching points. Special attention should be paid to disruptive technologies [Christensen, 1997; Christensen, Raynor, and Verlinden, 2001; Utterback, 1996]. Also, the research on the life cycles of product lines [Bass, 1969; Parker, 1992; Golder and Tellis, 2004] provides insight into the dynamics of pricing and thus the likely price trajectories affecting the value of alternative products.

### 4.3. Risks to LCV Determination

Our discussion so far has noted several qualities which must be quantified in the approach to measuring a system's LCV. Lack of thoroughness or care at any of these steps is a significant risk. Not identifying the right stakeholders, KPs, or preferences regarding the KPs will result in a flawed determination. Incorrectly specifying the way the system will satisfy stakeholders' preferences, or the system's inabilities to satisfy their preferences, present further risks to LCV. As system development organizations become more adept at measuring, evaluating, and delivering LCV, these risks will decrease as the organizations learn. Over time, templates of stakeholders, KPs, and typical preferences could emerge, along with checklists for verification and validation. While helpful, these should never become excuses for shortcutting the process. Meanwhile, other sources of future risk pertaining to the environment in which the system will operate—including government regulations, system usage patterns, and user demographics—are beyond designers' control and must be monitored carefully. However, even if it is impossible to predict specific changes, sometimes it is possible to anticipate the likelihood of some kind of change in a given area over a time horizon, in which case greater allowances can be made for general "buffers" of adaptability in a system design. de Weck and Eckert [2007] categorize some of the sources of uncertainty facing system designers.

Finally, because of the uncertainties and risks inherent in quantifying LCV, system developers should strive to identify the most significant sources of risk (i.e., uncertainty with consequences) in the LCV determination. If random variables (e.g., probability distributions) are used instead of point values in the LCV equation—a wise approach in our opinion—the variables contributing the most to variance in the overall LCV distribution can be found through an analysis of variance (ANOVA). Developers could calculate the expected value of perfect information (EVPI) in each area, and the value of a marginal improvement in each area, to determine how best to make investments in discovering additional information that will reduce uncertainty and risk.

## 5. CONCLUSION

We have presented a conceptual approach to quantify a system's LCV and illustrated it with an example. As this is an area where much further research is needed, we do not claim to have definitively solved the problem. We more modestly argue that our approach has merit as a foundation for further work, and our discussion brings to the table many important aspects of the problem from the wider marketing, value engineering, and quality communities. Designing systems for maximum LCV would seem to provide the potential for systems architects and engineers to provide dramatically increased value to their organizations and stakeholders, including society at large.

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## REFERENCES

Y. Akao (Editor), Quality function deployment: Integrating customer requirements into product design, Productivity Press, Cambridge, MA, 1990.

K.J. Arrow, Social choice and individual values, Wiley, New York, 1951.

P. Banerjee and O.L. de Weck, Flexibility strategy—valuing flexible product options, Proc INCOSE/ICSE Conf Synergy Between Syst Eng and Project Mgmt, Las Vegas, NV, 2004.

F. Bass, A new product growth model for consumer durables, Management Sci 15(5) (1969), 215–227.

B.L. Bayus, An analysis of product lifetimes in a technologically dynamic industry, Management Sci 44(6) (1998), 763–775.

R.C. Boas and E. Crawley, Divergence: The impact of lifecycle changes on commonality, Proc 17th Annu Int Symp INCOSE, San Diego, CA, 2007.

U. Bogenstätter, Prediction and optimization of life-cycle costs in early design, Build Res Inform 28(5/6) (2000), 376–386.

T.R. Browning, Modeling and analyzing cost, schedule, and performance in complex system product development, Ph.D. Thesis (TMP), Massachusetts Institute of Technology, Cambridge, MA, 1998.

T.R. Browning, On customer value and improvement in product development processes, Syst Eng 6(1) (2003), 49–61.

T.R. Browning and E.C. Honour, Measuring the lifecycle value of a system, Proc 15th Annu Int Symp INCOSE, Rochester, NY, 2005.

R.B. Campbell, Metrics for winning systems, Proc 2nd Eur Syst Eng Conf (EuSEC 2000), Munich, Germany, 2000.

A.B. Carroll and A.K. Buchholtz, Business and society, South-Western Educational Publishing, Mason, OH, 2006.

C.M. Christensen, The innovator's dilemma: When new technologies cause great firms to fail, Harvard Business School Press, Boston, 1997.

C.M. Christensen, M. Raynor, and M. Verlinden, Skate to where the money will be, Harvard Bus Rev 79(10) (2001), 73–81.

H.E. Cook, Product management: Value, quality, cost, price, profits, and organization, Kluwer, New York, 1997.

H.E. Cook and A. Wu, On the valuation of goods and selection of the best design alternative, Res Eng Des 13(1) (2001), 42–54.

J. Cutcher-Gershenfeld, F. Field, R. Hall, R. Kirchain, D. Marks, K. Oye, and J. Sussman, Sustainability as an organizing design principle for large-scale engineering systems, Proc Mass Inst Technol Eng Syst Div, Internal Symp, Cambridge, MA, 2004.

R. de Neufville and S. Scholtes, Maximizing value from large-scale projects: Implementing flexibility in public-private partnerships, Massachusetts Institute of Technology, Cambridge, MA, 2006.

O. de Weck and C. Eckert, A classification of uncertainty for early product and system design, Massachusetts Institute of Technology, Engineering Systems Division, Cambridge, MA, 2007.

O.L. de Weck, R.d. Neufville, and M. Chaize, Staged deployment of communications satellite constellations in low Earth orbit, J Aerospace Comput Inform Commun 1 (2004), 119–136.

H. Devine-Wright, D. Thomson, and S. Austin, Matching values and value in construction and design, Proc Environ Psychol UK (EPUK) Conf, Aberdeen, UK, 2003, pp. 42–51.

P. Doyle and J. Saunders, The lead effect of marketing decisions, J Market Res 22(2) (1985), 54–65.

J. Emerson, The blended value proposition: Integrating social and financial returns, Calif Management Rev 45(4) (2003), 35–51.

A. Engel and T.R. Browning, Designing systems for adaptability by means of architecture options, Syst Eng 11(2) (2008), forthcoming.

W.J. Fabrycky, B.S. Blanchard, and D. Verma, Simultaneously considering life-cycle cost and effectiveness for system design evaluation, Proc 9th Annu Int Symp INCOSE, Brighton, UK, 1999, pp. 521–529.

P. Fitch and J.S. Cooper, Life-cycle modeling for adaptive and variant design: Part 1: Methodology, Res Eng Des 15(4) (2005a), 216–228.

P. Fitch and J.S. Cooper, Life-cycle modeling for adaptive and variant design: Part 2: Case study, Res Eng Des 15(4) (2005b), 229–241.

R.E. Freeman, Strategic management: A stakeholder approach, Pitman Publishing, Boston, 1984.

T. Gilb, Software project management: Adding stakeholder metrics to agile projects, Proc 14th Annu Int Symp INCOSE, Toulouse, France, 2004.

P.N. Golder and G.J. Tellis, Growing, growing, gone: Cascades, diffusion, and turning points in the product life cycle, Market Sci 23(2) (2004), 207–218.

S.D. Green, Beyond value engineering: SMART value management for building projects, Int J Project Management 12(1) (1994), 49–56.

E.C. Honour, Optimising the value of systems engineering, Proc 11th Annu Int Symp INCOSE, Melbourne, Australia, 2001.

E.C. Honour, Understanding of the value of systems engineering, Proc 14th Annu Int Symp INCOSE, Toulouse, France, 2004.

K. Kalligeros, Using real options for engineering systems design: Framework, applicability and limitations, MIT Engineering Systems Division, Cambridge, MA, 2004.

K.C. Kalligeros and O.L. de Weck, Flexible design of commercial systems under market uncertainty: framework and application, Proc 10th AIAA/ISSMO Multidisciplinary Anal Optim Conf, Albany, NY, 2004.

R.L. Keeney and H. Raiffa, Decisions with multiple objectives: Preferences, and value tradeoff, Wiley, New York, 1976.

S. Kilcarr, Changing the box, Fleet Owner (2005), 44–48.

T.A. Kochan and S.A. Rubinstein, Toward a stakeholder theory of the firm: The Saturn partnership, Org Sci 11(4) (2000), 367–386.

N. Kulatilaka, The value of flexibility: The case of a duel-fuel industrial steam boiler, Fin Management 22(3) (1993), 271–279.

B. Larsen and D. Buede, An application of the CEaVa Method, Proc 10th Annu Int Symp INCOSE, Minneapolis, 2000, pp. 731–737.

LOGTECH, Life cycle management for design and maintenance, LOGTECH—Center of Excellence in Logistics and Technology, Chapel Hill, NC, 2002.

J.N. Martin, The seven samurai of systems engineering: Dealing with the complexity of 7 interrelated systems, Proc 14th Annu Int Symp INCOSE, Toulouse, France, 2004.

J.B. McConnell, A life-cycle flexibility framework for designing, evaluating and managing "complex" real options: Case studies in urban transportation and aircraft systems, Ph.D. Thesis (TMP), Massachusetts Institute of Technology, Cambridge, MA, 2007.

J. McManus, Managing stakeholders in software development projects, Elsevier Butterworth-Heinemann, Burlington, MA, 2004.

S. Mello, Customer-centric product definition: The key to great product development, AMACOM, New York, 2002.

R.K. Mitchell, B.R. Agle, and D.J. Wood, Toward a theory of stakeholder identification and salience: Defining the principle of who and what really counts, Acad Management Rev 22(4) (1997), 853–886.

E. Murman, T. Allen, K. Bozdogan, J. Cutcher-Gershenfeld, H. McManus, D. Nightingale, E. Rebentisch, T. Shields, F. Stahl, M. Walton, J. Warmkessel, S. Weiss, and S. Widnall, Lean enterprise value: Insights from MIT's Lean Aerospace Initiative, Palgrave, New York, 2002.

R. Nilchiani, D. Hastings, and C. Joppin, Calculations of flexibility in space systems, Proc 15th Annu Int Symp INCOSE, Rochester, NY, 2005.

R.J. Park, Value engineering: A plan for invention, St. Lucie Press, New York, 1998.

P.M. Parker, Price elasticity dynamics over the adoption life cycle, J Market Res 29 (August 1992), 358–367.

M. Pozar and H.E. Cook, On determining the relationship between vehicle value and interior noise, Proc SAE Int Cong Expo, Detroit, 1998.

S. Pugh, Total design: Integrated methods for successful product engineering, Addison-Wesley, Reading, MA, 1991.

E.S. Rebentisch, E.F. Crawley, G. Loureiro, J.Q. Dickmann, and S.N. Catanzaro, Using stakeholder value analysis to build exploration sustainability, Proc AIAA 1st Space Exploration Conf Continuing the Voyage of Discovery, Orlando, 2005.

F.Q. Redman and A.T. Crepea, A basic primer in life cycle cost analysis, Proc 16th Annu Int Symp INCOSE, Orlando, FL, 2006.

J. Ring, Discovering the value of systems engineering, Proc 10th Annu Int Symp INCOSE, Minneapolis, 2000, pp. 271–278.

W.B. Rouse and K.R. Boff, Strategies for value: Quality, productivity, and innovation in R&D/technology organizations, Syst Eng 4(2) (2001), 87–106.

T. Saaty, The analytic hierarchy process, McGraw-Hill, New York, 1980.

J.H. Saleh, Perspectives in design: The Deacon's Masterpiece and the Hundred-Year Aircraft, spacecraft, and other complex engineering systems, J Mech Des 127(5) (2005), 845–850.

J.H. Saleh, D.E. Hastings, and D.J. Newman, Flexibility in system design and implications for aerospace systems, Acta Astronaut 53(12) (2003), 927–944.

G.T. Savage, T.W. Nix, C.J. Whitehead, and J.D. Blair, Strategies for assessing and managing organizational stakeholders, Acad Management Executive 5(2) (1991), 61–75.

S. Scholtes, Flexibility: The secret to transforming risks into opportunities, Bus Dig (2007), 5–6.

A.P. Schulz, E. Fricke, and E. Igenbergs, Enabling changes in systems throughout the entire life-cycle—Key to success? Proc 10th Annu Int Symp INCOSE, Minneapolis, 2000, pp. 599–607.

M.R. Silver and O.L. de Weck, Time-expanded decision networks: A framework for designing evolvable complex systems, Syst Eng 10(2) (2007), 167–186.

A.J. Slywotsky, Value migration: How to think several moves ahead of the competition, Harvard Business School Press, Boston, 1996.

A.K. Stanke, A framework for achieving lifecycle value in product development, Master's Thesis (Aero./Astro.), MIT, Cambridge, MA, 2001.

R. Steiner, System architectures and evolvability: Definitions and perspective, Proc 8th Annu Int Symp INCOSE, Vancouver, BC, 1998, pp. 107–111.

J.D. Strauss and M. Radnor, Roadmapping for dynamic and uncertain environments, Res·Technol Management 47(2) (2004), 51–57.

E.S. Suh, O.d. Weck, I.Y. Kim, and D. Chang, Flexible platform component design under uncertainty, J Intell Manuf 18(1) (2007).

A.K. Sundaram, The corporate objective revisited, Org Sci 15(3) (2004), 350–363.

M. Thiry, Sensemaking in value management practice, Int J Project Management 19(2) (2001), 71–77.

D.S. Thomson, S.A. Austin, H. Devine-Wright, and G.R. Mills, Managing value and quality in design, Build Res Inform 31(5) (2003a), 334–345.

D.S. Thomson, S.A. Austin, G.R. Mills, and H. Devine-Wright, Addressing the subjective view of value delivery, Proc Cobra '03 Conf, Telford, UK, 2003b, pp. 197–213.

T.E. Trainor and G.S. Parnell, Using stakeholder analysis to define the problem in systems engineering, Proc 17th Annu Int Symp INCOSE, San Diego, CA, 2007.

J.M. Utterback, Mastering the dynamics of innovation: How companies can seize opportunities in the face of technological change, Harvard Business School Press, Boston, MA, 1996.

E. von Hippel, "Lead users: A source of novel product concepts," Readings in the Management of Innovation, M. L. a. W. L. M. Tushman (Editor), HarperBusiness, New York, 1986, pp. 352–366.

T. Wang, Real options "in" projects and systems design—identification of options and solution for path dependency, Ph.D. Thesis (E.S.D.), Massachusetts Institute of Technology, Cambridge, MA, 2005.

J.M. Warmkessel and R.A. Slack, Using value to define system requirements, Proc 13th Int Conf Syst Eng (ICSE99), Las Vegas, 1999.

R.B. Woodruff and S.F. Gardial, Know your customer: New approaches to understanding customer value and satisfaction, Blackwell, Cambridge, MA, 1996.

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