2007 Society for Design and Process Science
Printed in the United States of America

DYNAMIC OPTIMIZATION OF SYSTEMS OF SYSTEMS USING VALUE MEASUREMENT

Eric C. Honour
Systems Engineering & Evaluation Centre, University of South Australia, Adelaide, Australia
Honourcode, Inc., Pensacola, FL, USA

Tyson R. Browning
M.J. Neeley School of Business, Texas Christian University, Fort Worth, TX, USA

Many systems of systems (SoS) occur today through the collaboration of multiple stakeholders, without any clear authority or direction at the SoS level. Examples include a supply chain, an airport, and the Internet. Because of the uncontrolled interactions, such a SoS exhibits complexity behaviors such as reflexivity, emergence, self-organization, and adaptation. This paper presents underlying theory to explain a methodology for ***dynamic optimization*** *of SoS, in which the stakeholders make changes based on local perceptions of the value of the SoS. Each stakeholder has a different local perception of value, measured against an objective function that may be unique to the stakeholder. As the stakeholder compares perceived value to desired value, the stakeholder attempts to optimize the SoS from its own point of view by making decisions that lead to SoS changes. These changes then affect other stakeholders, resulting in a dynamic architecture and implementation of the SoS. We present the optimizing value proposition of each stakeholder in terms of a quantifiable objective function based on the life-cycle value of the SoS to that stakeholder, and we present the dynamic interaction as a model of self-organization. An example based on supply chain management demonstrates the approach.*

Keywords: *systems of systems, complexity, complex adaptive systems, optimization, value*

1. Introduction

Current emphasis in systems engineering (SE)[1] has been shifting to the field of “systems of systems” (SoS), in which many independent systems interact with each other to perform higher-level functions. Some examples of SoS are:

- **Supply Chain Management** (SCM), in which end manufacturers influence their suppliers to enable improvement of their own inventory costs and responsiveness. Suppliers are motivated to interact with the manufacturers to improve their own sales and profitability. Each organization has its own control systems, independently managed and improved, and the various control systems communicate with each other in networked interaction.
- **Audio/Video Distribution**, in which end consumers obtain digitized audio/video files to play on personal electronic devices. Interacting systems in this SoS include the personal players, personal computers that download and store the files, web site systems to sell the files, copyright control systems, artists who are content providers, and the laws that protect the

---

[1] An acronym list is provided for reference at the end of the paper.

intellectual property. Each of these systems is independently controlled for purposes that go beyond the personal electronic devices, yet they interact to provide this one method of audio/video distribution.

- **Military Forces**, in which many special-purpose systems independently provide mobility (ships, airplanes, vehicles), sensing (radio, radar, sound, infrared, satellite), weaponry, and command and control. Each system is defined and developed under government acquisition control driven by budget considerations, yet the systems today interact with each other through sophisticated communications networks that create a cohesive military force with astonishing responsiveness and capabilities.
- **Airports**, in which the component systems include aircraft, support/maintenance, baggage handling, air traffic control, ground infrastructure (taxiways, runways), ticketing, gate control, boarding bridges, transportation security, parking, auto traffic control, shopping, and pedestrian control. As with other SoS, each system is typically developed independently. Many systems are procured by completely different agencies (the airport authority, airlines, transportation security), having to meet a myriad of government regulations and standards, yet they interact with each other in sophisticated and subtle ways to provide a "total passenger experience."

In some domains of controlled SoSs, SoS engineering (SoSE) is viewed as simply a higher form of SE. In military systems development, for example, the government acquisition agencies define and control the capabilities of the SoS, allocating those capabilities into the individual systems. Although systems are developed and procured independently, the higher-level SoS control provides constant direction and guidance to the many system development efforts. In such a case, SE tools and practices are simply expanded to meet the broader need, using methods such as Capabilities Engineering (Ravichandar, 2007) and the Department of Defense Architecture Framework (DODAF) (DoD, 2007).

In the more general case of the uncontrolled SoS, however, SoS "engineering" is nearly an oxymoron. Because of the independent management of the systems, there is usually no central control. Rather than being engineered, the SoS development occurs through dynamic interaction of the many system stakeholders. In the largest possible example, the Internet continues to grow and change without any central control authority. (Even the most central authority in the Internet, the control of domain names or URLs, is handled by several agencies in collaboration.) Individual systems change in response to (a) system stakeholder desires, as influenced by (b) other changes in the SoS itself.

The scope of this paper is aimed at this general case in which SoS development happens through the interaction of many independent agencies. Each agency views the SoS in terms of its utility to that agency, seeking to "optimize" the SoS (from its point of view) through the influences available to it. We explore the dynamics of such interactions from the viewpoint of the desired optimization.

The interactions that occur in this situation fall very clearly into the realm of complexity theory (Waldrop, 1992). Complexity occurs when multiple agents reflexively interact through a common structure, and studies in complexity show that many of the resulting behaviors and outcomes are counter-intuitive. These behaviors frequently influence the SoS optimization.

In this work, we explore the behaviors of such an uncontrolled SoS. We synthesize theories and techniques from three different streams of literature: (a) SE (and the recent emphasis on SoSE); (b) valuation and optimization; and (c) complexity theory. In the next sections, we will briefly review each of these areas. The paper also draws from the marketing literature and stakeholder theory, which we will mention later. We show how the behaviors in an uncontrolled SoS operate at the conjunction of SE, value measurement and complexity theory. Through an example based on SCM, we define and demonstrate the principle of dynamic optimization, in which the dynamic interactions of all SoS stakeholders, each attempting to optimize the SoS for their own purposes, results in forward movement of the SoS itself.

Beginning with the foundational theory, the following sections of the paper build to the principle of dynamic optimization. We start by identifying relevant literature and thoughts in the source areas (SE, value/optimization, and complexity), with some additional specific expansion in complexity theory and SoS. Then we demonstrate a SCM example of a complex, uncontrolled SoS, showing the types of stakeholder interactions that cause change in the SoS. Finally, we define dynamic optimization and show how stakeholder interactions result in the incremental, mutual improvement of the SoS.

2. Systems Engineering

SE has been recognized for over 50 years (Honour, 1999, Goode, 1957) as an inter-disciplinary approach to developing successful systems. However, SE is still treated primarily as heuristics learned by each practitioner during the personal experimentation of a career. The heuristics known by each differ, as shown by the fractured development of SE "standards" and SE certification (Honour, 2006). Current competing standards include ANSI/EIA-632, IEEE-1220, ISO-15288, Capability Maturity Model Integration (CMMI)[2], MIL-STD-499C, and others. These standards provide indication of good practices that are agreed by the authors of the standards, but the differences in the standards signify the lack of agreement about the discipline. Perhaps the best current definition of the field is contained in the INCOSE Systems Engineering Handbook (INCOSE, 2006).

A common ontology for SE, obtained through evaluation of the differing standards (Honour, 2006), shows that it embodies practices that (a) define the operation to be performed, (b) define detailed requirements for the system, (c) synthesize an architecture of components and services that can meet the requirements, and then (d) implement that architecture through engineering design, procurement, and training. These four development practices are further supported by guiding practices of (e) technical analysis to predict system performance, (f) verification (against requirements) and validation (against the operation) at frequent points, (g) scope management and control, and (h) technical management of the in-process efforts.

Primary recent efforts toward SoSE follow the same practices, defining higher-level SE that can effectively apply to SoS development when it has some form of central control. The U.S. Department of Defense has published a preliminary guide to SoSE (DoD, 2006) that considers each SE activity from the viewpoint of SoSE, providing guidance on how to tailor the activities. Only within the last year has much SE research turned to the aspects of complexity theory that inform the behavior of most SoSs.

3. Value and Optimization

Much research has been done on the subject of quantifying value during the design process, starting with the field of decision theory (e.g., Wald, 1947). Browning and Honour (2005) provide an extensive list of references that give insight into the perception of life-cycle value, some of which is reviewed here as applicable to the current effort.

A project at Loughborough University, Value in Design (VALiD)[3] explores how stakeholders articulate their preferences and how designers respond to them in the building construction industry in the UK. Among other efforts in VALiD, Thomson et al. (2003a, 2003b) strive to show that there is more to value than functional interpretations and measurements. In separate efforts, Cook and his colleagues (Cook, 1997, Cook& Wu, 2001) explore methods for quantifying the value of a system during the design phase.

From a 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.

---

[2] "Capability Maturity Model," "Capability Maturity Model Integration," and "CMMI" are registered trademarks of the Carnegie Mellon University Software Engineering Institute.

[3] www.valueindesign.com

Honour (2001, 2004) and Ring (2000) explore the value of SE and “how much” SE is appropriate for a project. 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.

Customers are the primary stakeholder, and the vast marketing literature has much to say about what customers and markets value and prefer. 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). 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.

4. Complexity Theory

Complexity theory is somewhat newer than SE, arising out of interesting and puzzling observations about the behavior of seemingly-simple structures. Study of cellular automata in the 1960s and 70s (e.g., von Neumann 1966) showed that surprisingly unpredictable results can often occur through the use of simple rules of interaction. The more theoreticians studied the field, the more they found behavior that simply could not be explained with traditional theories.

The field of complexity theory has been largely a descriptive research centered on economics, mathematics, and physical phenomena. Much work has been centered on the Santa Fe Institute that has invited key figures from many disciplines to work together to discover common effects in their disparate fields. A historical reference (Waldrop, 1992) provides insight into the growth of the field, while one recent extensive presentation (Grisogono, 2005) contains an excellent summary of the current state of knowledge as applied to systems. One particular aspect of complexity theory deals with complex adaptive systems (CAS). In one SoS area, Choi et al. (2001) explore the impacts of complexity on SCM issues, highlighting the dynamic nature of the SoS growth and how that nature is described by CAS theory. Within the last two years, new efforts are exploring the impacts of complexity theory on SE, bringing together SE practitioners and complexity theorists. We will provide a top-level description of the concepts as they apply to our work.

Complexity behavior falls between the extremes of chaos and determinism. At one extreme, chaos theory (which is not complexity) deals with situations in which the behavior of the elements is completely random and unpredictable, as in the Heisenberg Uncertainty Principle. In such cases, however, the mathematics of probability and statistics can apply to make useful predictions of the aggregate behavior. At the other extreme (also not complexity), many systems seem to be composed of elements with predictable behavior. The engine of an automobile, for instance, continues to provide rotary power so long as it is intact and supplied with fuel, air and exhaust. Behavior of the automobile as a whole is predictable based on the predictability of its elements. The field of complexity has often been characterized as operating at the “edge of chaos” between these two extremes (Waldrop, 1992). Complexity occurs in systems that have sufficient chaos to be puzzling, and yet sufficient order to provide recognizable patterns. This is an interesting and useful place for systems to lie, because complexity causes a delicate balance between order and chaos that creates the desirable traits of spontaneity, adaptation, and “life.” Because of their aspects of order, complex systems have enough stability to persist in patterns of behavior, even when their components may change. Because of their aspects of chaos, complex systems have enough changeability to respond and survive through varying environments. The results are systems that exhibit dynamic characteristics that are very useful.

Agents. Complexity often happens because the structure is made of many interacting parts. Such parts can often be viewed as relatively independent “agents” that work together to produce the emergent properties. Each agent operates to perform its appropriate functions, and it is through the interactions that the emergent properties appear. In the stock market, each investor and each public corporation are such agents. The investors buy and sell shares. The corporations provide or retain information about their operations. Each agent, investor or corporation, is trying to achieve a better profit from their participation in the market.

Reflexivity. A typical characteristic of complexity occurs in the reflexive nature of the interactions. The essence of reflexive interactions is that the actions of each agent cause other agents to respond in ways that affect the original agent. In the purest sense, the agents in a reflexive interaction have no knowledge of the actions performed by other agents and can only respond to the effects of those actions. Each agent acts, and its actions have impacts on the other agents around it. Other agents act in response to the change in their own environment (the original agent being part of their environment), thereby changing the environment for the original agent. Thus, in a complex structure there are many feedback paths that cause reflexive interactions to abound. The classic cold-war dark comedy movie Dr. Strangelove was an example of such a reflexive complex system, in which each person in the interaction escalated their actions based on their own perceptions of the actions of the enemy. This behavior was a key part of the artificial intelligence discussions prompted by Hofstadter (1979).

Local Information. In such a structure of agents and reflexive interactions, it is also usual for the agents to operate on local information rather than global information. Most complex structures have far too many agents for anyone to fully understand the entire structure. In the Internet, for instance, each computer communicates with only a few other computers at any given time. The responses and operation of each computer are therefore governed only by the environment evidenced by those few.

Emergent Properties. Emergent properties are those behaviors that are perceptible only at the system level and cannot be perceived or even predicted from the behaviors of the parts. An automobile is made up of wheels, chassis, engine, interior, controls, etc., yet none of these parts provide the capability to transport people from one place to another, an emergent property of the entire automobile. Emergent properties may be useful and designed, as in this property of the automobile, or they may be destructive or surprising behaviors, as shown in Table 1. In the design of systems, it occurs often that once-surprising emergent properties later become ordinary designed properties. In the automobile examples of Table 1, for instance, early automobiles did not provide a "quiet place," but once this emergent property was discovered it became a significant design issue to improve it.

Table 1 Types of emergent properties (examples from an automobile).

	Useful	**Neutral**	**Destructive**
Designed	Desired capabilities *(Ex: transportation)*	Facts of design *(Ex: physical size)*	Accepted trade-offs *(Ex: braking distance)*
Surprise	Exploitable features *(Ex: quiet place)*	Facts of existence *(Ex : heat generator)*	Fearful features *(Ex: killing potential)*

Self-Organization. Some types of complex systems frequently exhibit self-organization, even on very basic levels. This is particularly true for systems made up of independent agents operating on local information. Termite mounds appear to be organized at a high level, resulting in towers and pillars of sand that can approach castle proportions, yet the mounds are created by individual insects gluing each grain of sand into place using apparently simple rules and local information. In mathematics, a similar self-organization appears in fractal diagrams.

Complex Adaptive Systems. At the highest level, complexity often leads to adaptation, in which the complex structure changes to better fit its environment. Adaptation happens when the structure has self-modifying abilities, local information, and some self-attaining measure of fitness. The complex structure responds to environmental inputs that act either as threats or opportunities against the measure of fitness. As a result, the complex structure modifies itself to enhance its fitness. An obvious example of this is life, in Darwin's descriptions of *The Origin of Species* (1859). Other examples also abound, however, including seemingly-simple structures such as agent-based models and very large structures such as military information networks. CASs are the result of bottom-up interactions of the agents in the system, as opposed to the top-down design methods of classical SE. CASs occur in response to the tension among four mechanisms (Waldrop, 1992):

- *Positive feedback* [4] – a mechanism that seeks to reach for improved behavior against the measure of fitness. (Airport SoS Example: passengers booking flights)
- *Negative feedback* – a mechanism that seeks to limit growth against the measure of fitness. (Airport SoS Example: overcrowding, delayed flights)
- *Balance of exploration and exploitation* – a mechanism that causes variation through trial-and-error, incurring the constraints of positive and negative feedback. (Airport SoS Example: weather impacts, passengers seeking successful routing, airlines seeking successful flights.)
- *Multiple interactions* – a mechanism to cause frequent action so that the exploration and exploitation happen more quickly than the stabilizing behaviors. (Airport SoS Example: large numbers of passengers, flights.)

When all four of these mechanisms exist, then the self-organization of a complex system moves into the realm of CASs. These characteristics of CASs are of most interest to us, because a SoS without central control develops through these mechanisms.

5. Systems of Systems

In efforts largely separate from complexity theory, systems engineers have been pursuing issues related to SoSs. The primary motivation for SoS work has been a recent, significant change in the character of systems due to the rapid development of networked connectivity. This connectivity has offered new capabilities of communication and functionality that are extremely attractive to system users in many domains. SoS examples given in the Introduction show the kinds of new functions never before available.

This change has been extremely rapid in historical terms. In only ten years, the character of systems has changed from individual functionality to connected functionality. As shown in Figure 1, systems development is at a nexus of growth that seems as important as the industrial revolution of the 1800s and the computer revolution of the mid-1900s. With the advent of effective networking, system capabilities are rapidly reaching unprecedented combinations.

The definition of SoS has been discussed by many (e.g., Boardman et al., 2005). While it is easy to recognize a SoS as a system made up of lower-level systems, this simple approach is inadequate to characterize the important differences, because nearly every system, even to the most simple, can be so described. The most authoritative definition is attributed to Mark Maier (see Levis et al., 2004, Maier 2007, and recognition in Wikipedia, 2007), suggesting that a SoS is best recognized by the significant presence of the following five characteristics:

- Operational independence of the elements, in that component systems achieve well-substantiated purposes even if detached from the SoS,
- Managerial independence of the elements, in that component systems are developed and managed for their own purposes,

---

[4] This use of "positive feedback" and "negative feedback" is different from usage in classical control theory, in which negative feedback seeks to minimize an error function while positive feedback magnifies the error function.

- Evolutionary development, in that the functions and purposes are added, removed and modified in an ongoing way,
- Emergent behavior, in that the SoS performs functions that are not achievable by the component systems acting independently, and
- Geographic distribution, in that the geographic extent of the SoS forces the elements to exchange information in a remote way.

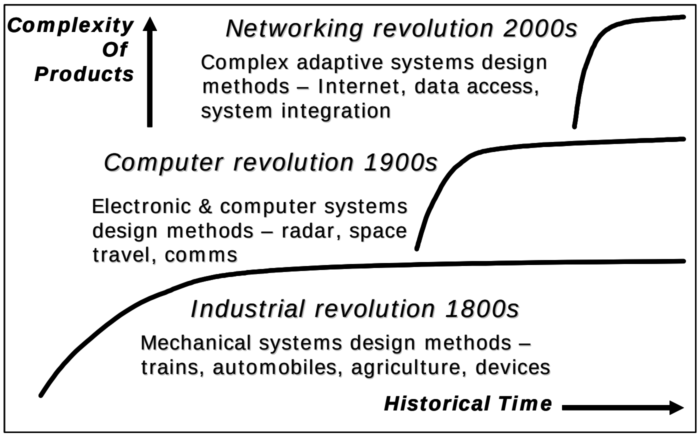

Fig. 1 Explosive growth of complexity.

When these characteristics exist to a greater rather than a lesser extent, then the SoS exhibits behaviors that are difficult to control through traditional SE methods. Many of the behaviors are described by complexity theory. Two major classes of SoS may be observed:

Controlled SoS. In some domains, ownership of the component systems is held by a common, higher-level entity, even though the individual systems are managed independently. In the examples in the introduction, this is certainly true of a military force, in which the entire force, its development, and its operation are all owned by the defense organization (e.g., the U.S. Department of Defense). This same nature is also somewhat true for audio/video distribution (major development performed by Apple Computers through coordination with many other companies) and an airport (coordinating agency is the airport authority), although in both of these cases there are many component systems that are developed and installed by completely independent owners.

In such a controlled SoS, the owning organization can provide influence and guidance to the independent developments, sometimes with significant managerial force. When the SoS is viewed from this top-down approach, SoSE appears to be merely a larger form of SE, with adaptation for the difficulties of managerial communications. In the U.S. DoD, for instance, the Joint Forces Command (JFCOM) provides central definition of military capabilities, review of system development plans, and interoperability tests of new or changed systems. The method used by JFCOM to guide this activity is the Joint Capabilities Integration and Development System (JCIDS), a higher-level form of SE characterized by reliance on the usual decomposition of the widely-known “Vee Model” of SE (INCOSE 2006, p.3.6) and using the many system architecture views of the DODAF (DoD, 2007).

Uncontrolled SoS. In most domains, however, there is no SoS central control. Rather, the SoS grows as an opportunistic aggregation of component systems. In the examples in the introduction, supply chains (SCs) are usually such an uncontrolled SoS. Audio/video distribution and an airport also exhibit uncontrolled development through the actions of organizations who own add-on or competitive systems within the SoS. Much of complexity theory has been developed from the viewpoint of economic systems that are exactly this form of uncontrolled SoS.

As an example of uncontrolled SoS, SCs offer insight into the behavior. SC management (SCM) has spread widely since the 1980s through a desire on the part of manufacturers to reduce the cost of their parts inventory without increasing the risk of production stoppage. In the basic idea, the manufacturer creates a long-term “preferred supplier” relationship with key parts suppliers, in which the manufacturer and suppliers cooperate to reduce duplicative inventories. To achieve this effect, the manufacturer’s production management systems and the supplier’s inventory management systems are connected electronically so that the supplier can act as a real-time inventory of production parts. Both companies benefit from the arrangement. The manufacturer drastically reduces parts inventory with only a slightly increased risk of production stoppage, while the supplier obtains greater assurance of market share and better demand forecasting, which in turn results in significantly reduced material inventory costs. Of course, these benefits can also result in detriments such as collusion, loss of competition, and higher pricing.

What complicates the issue and turns such an arrangement into a SoS is that there are many manufacturers and many suppliers. While some notable SCs have a strong “captain” (such as Dell or Wal-Mart) that dictates rules for network participation, most companies do not even realize the full extent of the supplier networks in which they are enmeshed. As the idea took hold, software tool vendors offered this connectivity as part of their financial and inventory management systems, and the application became widespread. The benefit was large enough that companies felt competitive pressure to participate. Further steps included shipping agencies in the parts control methods, so that the production parts inventory became divided among the manufacturers, the suppliers, and the shipping between them. This required even more sophisticated software tools resident at all three types of companies. Some manufacturers began exploring second-tier and further suppliers, trying to manage the entire supply network to smooth fluctuations in the supply of materials and parts – a kind of virtual vertical integration.

In such an uncontrolled SoS, each participant contributes to the SoS because of the benefits that accrue to them. In addition to the manufacturers’ and suppliers’ benefits mentioned above, shipping companies increase their market share through dynamic tracking services beyond the simple transportation of goods. Software tool vendors create and build a business niche.

The SoS grows through the actions of all the stakeholders. There is no central control. Coordination occurs through the mutual development of interface and functionality standards for the networked tools, driven by the marketplace that demands more and better capability. Each participant modifies its own systems through internal development or external purchase. As the networked systems change, other participants respond to the change by incorporating further capabilities. Changes occur in response to locally-perceived environmental changes, but each change has impacts on the entire network, often causing recursive responses that propagate widely.

6. Value Measurement by a Stakeholder

Because change in such a system occurs through the actions of each stakeholder, it is important to understand how stakeholders perceive value. In this section, we summarize the work in Browning and Honour (2005) showing how stakeholders measure the life-cycle value (LCV) of a system, with modifications that apply the principles of that work to the interesting issues of uncontrolled SoS. The LCV measurement is demonstrated by reference to a new example of a generic SC that emphasizes behaviors germane to the current work.

The perceived value of a system can be quantified in terms of a set of key parameters (KP) that change across stakeholders and time. These KPs represent the subjective preferences of the various stakeholders and thereby indicate their perception of value. This quantification requires the following steps:

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

6.1. 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 that has a vested interest in a system. Stakeholders are those who are willing to act in some way to preserve their interest (hence "vested" interest). In general, stakeholders include those who derive some benefit from the system (positive stakeholders) and those who make some sacrifice for the system (negative stakeholders). A few examples of stakeholders and their actions include:

- 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, and
- A firm that derives revenue from the sale or ongoing operation or use of the system and perhaps from periodic upgrades.

Example: Stakeholders of the SC SoS. For our example SoS of a SC, we wish to focus on the stakeholders who are also agents in the SoS, who have the power to change the SC. Some of these stakeholders include:

- Manufacturers
- Suppliers
- Transportation agencies
- SCM software tool vendors

We note that these are classes of stakeholders rather than monolithic entities. For example, manufacturers have a variety of wants and needs in terms of required parts, rate of supply, response times, etc. Commercial analysis will often 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.

6.2. Identify System KPs

Unlike most engineering parameters, value is a perceived quantity stemming from subjective preferences. Stakeholder preferences are distinct and different from requirements. Requirements are relatively objective and specify acceptability. Values express subjective preferences among alternatives. Preferences emanate from individuals, which makes them less amenable to firm analysis

---

[5] The word "value" is used herein with two distinctly different meanings. In the first meaning, as used in items 4 and 5 above, we refer to the "value" of a system to its stakeholders, which is a subjectively perceived quality of the system. In the second meaning, we refer to the "value" of a parameter, which is a simple mathematical quantity. The reader should be aware of this difference to reduce confusion.

than quantities like size, weight, or speed. 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). The KPs are usually operational in nature because stakeholders are interested in the operational results rather than the technical implementation. From our SC example, parts lead-time is an operational parameter used by a manufacturer to measure SC responsiveness; transportation mode is a technical parameter. The first might be a KP for a manufacturer; the second is not.

Two broad categories of system attributes are benefits and sacrifices. 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 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, an SCM tool with a high acquisition cost may be a benefit for the tool vendor and a sacrifice for its customer. (The sacrifice for the customer may be outweighed by other KPs that benefit as a result of buying the tool.)

The KPs are frequently different for different stakeholders, and may even conflict. In the case of our example, for instance, parts inventory cost is a KP for the manufacturer while product inventory cost is a KP for the supplier. Manufacturers would prefer to reduce their parts inventory cost by having suppliers with parts immediately available (short lead-times), thereby increasing the product inventory or shipping costs for the suppliers. Such a conflict in the complex network of a SC may be resolved by allowing the supplier to have better visibility of the manufacturer need, thereby also reducing the supplier inventory.

Example: SC KPs. Identifying the KPs for the SC SoS 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 SCM system better than another?" Table 2 is a representative list of KPs. Note that this list has been simplified for illustration; many of the parameters shown would have much better definition than is evident here, and there are other KPs for each stakeholder.

Table 2 KPs for the example SCM system.

Manufacturers • Parts inventory cost • Parts lead-time	**Transportation Agencies** • Transported tonnage • Responsiveness
Suppliers • Product sales • Product inventory cost • Responsiveness	**SCM Tool Vendors** • Software sales • Return on investment

There are several characteristics to note in Table 2 that highlight difficulties in this process of identifying subjective preferences. These difficulties impact the dynamic optimization to be described later.

(1) Note the large number of different parameters. Stakeholders have highly varied preferences for any given system.

(2) 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.

(3) Some parameters are shared by several stakeholders, but they may be interpreted differently.

(4) Some parameters conflict across the stakeholders (e.g., “parts inventory cost” for the manufacturers against “product inventory cost” for the suppliers).

The result of these issues is that agreement on and quantification of the KPs can be a difficult process. There are crucial issues in this agreement. In the steps that follow, we demonstrate the use of the simple method of weighted averages to combine the KPs into a holistic measure, yet this is only one method available – and no method completely represents the details of individual preferences. Even using this simple method, the process of quantifying the KPs can be agonizing. Federations in some SoSs help to create agreement, as in the members of the Organization of Petroleum Exporting Countries (OPEC), or the technical standards bodies of an industry organization. The SC example has been chosen as one in which these agreements are least controlled, demonstrating the bottom-up process of an “uncontrolled SoS.”

6.3. 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 value of the KP in the eyes of the stakeholders. This preferred value 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. The quantified value of the parameter is therefore most effectively considered to be a stochastic variable. This variable may be modeled at various levels of depth as for any other stochastic variable: by a single value 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 effective method frequently used in risk management is to describe the value by a triangular distribution of mode, smallest, and largest as shown in Figure 2. For a “larger is better” (LIB) parameter, the smallest value is a pessimistic estimate and the largest value is an optimistic estimate. For a “smaller is better” (SIB) parameter, these estimates are reversed. In either case, the mode is an estimate of the single most frequent value.

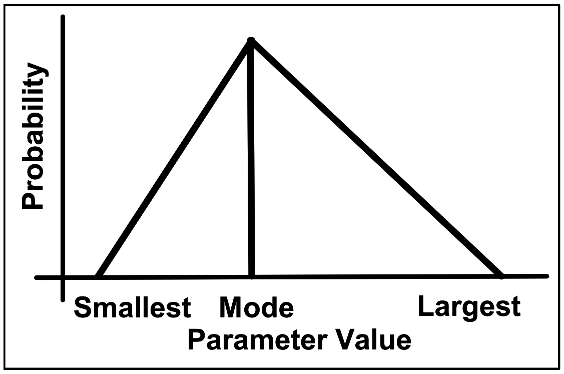

Fig. 2 Representing a quantified parameter using a triangular distribution (figure adapted from Browning and Honour (2005)).

For measuring LCV, however, it is insufficient to quantify the parameters at a single point in time. Stakeholder preferences change over the lifetime 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 or purchase profiles; the stakeholder preferences for the future may be modeled using predictive assessments and trends, tempered with strategic judgment.

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

Example: SC KP Quantification. Figure 3 shows a typical quantification of one KP for one stakeholder: the annual product sales for a single supplier. The figure represents the incremental utility of each value of sales to the supplier's stakeholders. The triangular distribution for each year shows values that range from unacceptable to fully satisfying. Historical data may be based on the records of shareholder and corporate officer preferences, with the mode for each year given by the actual value of annual sales. Projected data may be based on strategic objectives. Such a stochastic representation may be plotted for each KP and for each stakeholder group. Note that values will be different for different suppliers (and different manufacturers, transporters, and tool vendors), because each supplier has its own stakeholder group.

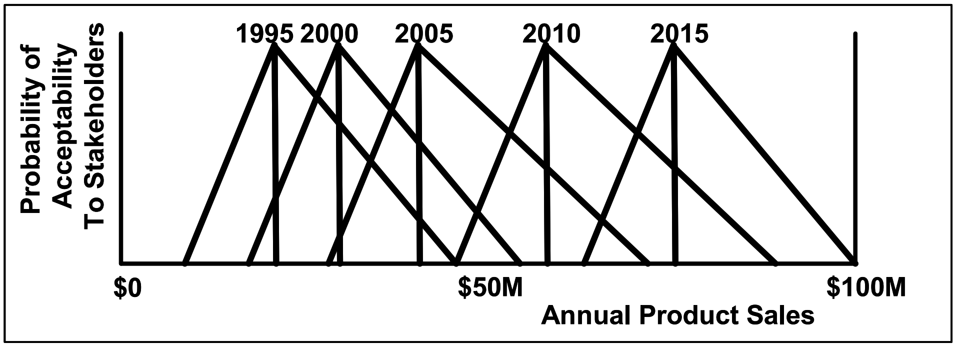

Fig. 3 Typical predictive quantification of one KP (figure adapted from Browning and Honour (2005)).

6.4. Create a Holistic Measure of Stakeholder Value

With a quantified understanding of the KPs that matter to each class of stakeholders, we can define a holistic measure of system value to the stakeholders by combining these many KPs into a single measure. This procedure follows the well-known axiom of multivariate decision theory, that optimal decisions cannot be made based on a vector of multiple parameters (Arrow 1951). In any decision, the parameters are combined in some fashion into a single measure of value. If this combination is not performed explicitly (e.g., by voting), it is still performed implicitly by the decision-maker.

One mathematical method used to combine multiple parameters into a single measure of value 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. 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 as in Figure 3, then the system preferred value is a probabilistic combination of the parameters. The weights themselves can also be stochastic variables, but the combinatory procedure remains the same. This process was partially described in Honour (2001) as a quantified Objective Function for the system. Browning and Honour (2005) expanded the concept to include the complexity of the KPs preferred by different stakeholders and the changes in those KPs over time. 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/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 of these challenges is provided in (Browning 1998, Ch. 7).

Example: Value of the SC to different stakeholders. For our SC example, we assume illustrative values for the weights, the parameter preferences, and the actual system parameters. Table 3 shows a set of values that represent the value of the SC SoS to some of the many different stakeholders at one point in time.

Table 1 Typical Analysis of Instantaneous SoS Value to Different Stakeholders (figure adapted from Browning and Honour (2005)).

		Preferences			Value to Stakeholder Groups				
Parameter	**Units**	**Worst**	**Mode**	**Best**	**Weight**	**Actual Value**	**Utility Level**	**Weighted Value**	**Notes**
Manufacturer A									Very dissatisfied (<<1.0) with current SC; inventory cost is high and parts lead time is also high.
Parts inventory cost	$M	70	40	30	70%	55	**0.50**	0.35	
Parts lead time	Days	10	5	0	30%	7	**0.60**	0.18	
Perceived Value								**0.53**	
Manufacturer B									Quite satisfied (>1.0) with current SC; not likely to fund changes at this time.
Parts inventory cost	$M	8.0	5.0	3.0	80%	4.5	**1.25**	1.00	
Production stoppage risk	Stops/ K-hrs	15	10	0	20%	8	**1.20**	0.24	
Perceived Value								**1.24**	
Supplier 1									Quite satisfied (>1.0) with place in current SC; good sales and responsiveness, but could reduce inventory cost
Product sales	$M	30	35	50	50%	45	**1.67**	0.83	
Product inventory cost	$M	4.0	2.0	0.5	30%	3.0	**0.50**	0.15	
Responsiveness	Days	10	4	1	20%	3.0	**1.25**	0.25	
Perceived Value								**1.23**	
Transport α									Highly dissatisfied (<<1.0) with current SC; responsive to clients, but not getting the tonnage
Transported tonnage	K-ton	10	25	40	80%	12	**0.13**	0.11	
Responsiveness	Days	6	2	0.5	20%	1.5	**1.33**	0.27	
Perceived Value								**0.38**	
Tool Vendor א									Mildly dissatisfied (<1.0) with current SC; both sales and ROI are lower than desired.
Software sales	$M	6	8	12	60%	7.5	**0.75**	0.45	
Return on investment	%	0	15	50	40%	11	**0.73**	0.29	
Perceived Value								**0.74**	

For each parameter that was identified, Table 3 shows the preferences quantified in the indicated units. In each row, the “Worst” column represents the value that is least preferred by that group of stakeholders, while the “Best” column represents the value that is most preferred by the stakeholders. The most likely acceptable value is in the “Mode” column. Note that some sets of preferences operate in a LIB direction, while others operate in a SIB direction. The “Weight” column is the assessed weight of that parameter to the stakeholder group. This is followed by the actual value of the parameter in the current system and a normalized calculation of that value against the stakeholder preferences.

There are many mathematical methods to normalize the actual value against the preferences. In this example, we have chosen to calculate the normalized value against the triangular distribution by arbitrarily assigning utility level 0.0 to the Worst value, utility level 1.0 to the Mode value, and utility level of 2.0 to the Best value. Values between these assignments are interpolated linearly. By this assignment, a value rating of 1.0 represents a case in which the system meets the stakeholder preferences. Values between 0.0 and 1.0 represent cases in which the system falls short of the preferences, while values between 1.0 and 2.0 represent cases in which the system has added value.

6.5. Measure Stakeholder Value over Time: Life-cycle Value

The holistic measure of system value can be extended to create a measure of LCV by integrating or summing the measure over the system's expected lifetime:

$$LCV = \sum_{Inception}^{Disposal} TotalValue \tag{1}$$

Browning and Honour (2005) show the typical behavior of LCV over time. 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 1.0 for each year in which the system meets the preferences of the stakeholders. A system that exactly meets the stakeholder preferences for 15 years has a LCV of 15; a system that partially meets the preferences (Value = 0.75) for 20 years also has a LCV of 15. As defined, LCV accounts for adaptations to stakeholders' dynamic preferences: a system that does not change can be expected to decrease gradually in value as the stakeholders' lists of wants and needs grows.

For the purposes of the current work, we are interested in the way in which stakeholders act to change the SoS in which they exist. As the incremental LCV begins to diminish, the overall projected LCV for the SoS becomes less attractive. As with several of the stakeholders in Table 3, dissatisfaction with the SoS becomes the impetus to change.

Example: Supply Chain LCV. Table 4 shows how the annual perceived value provides this impetus for key managerial and technical decisions. The table shows a set of historical and predicted values for the SC for two manufacturers over a ten-year period. Planned or actual upgrades to the SC are indicated with boxed borders.

Table 4: Example SC LCV as Perceived by Two Manufacturers. Boxes indicate upgrades to existing SCM systems (figure adapted from Browning and Honour (2005)).

Year	'03	'04	'05	'06	'07	'08	'09	'10	'11	'12	Total LCV
Mfg A											**8.55**
History	1.03	0.93	0.84	0.76	0.53						4.09
Predict						$\boxed{0.94}$	0.87	0.83	0.77	$\boxed{1.05}$	4.46
Mfg B											**11.21**
History	0.89	$\boxed{1.05}$	1.00	$\boxed{1.31}$	1.24						5.49
Predict						1.18	1.12	1.05	$\boxed{1.22}$	1.15	5.72

Manufacturer A has approached their SC with benign neglect for some years, suddenly discovering that their value measurements (see Table 3) are very unsatisfactory. Some future upgrades have been planned for 2008 and 2012, but even these appear to be inadequate. As a result, their ten-year LCV scores only 8.55 against a desired value of 10. Manufacturer A is very likely to change its current plans and to implement radical changes to its SC or SCM in the near term.

Manufacturer B has made regular upgrades to its SCM approach. Each upgrade results in a SC (SoS) that better satisfies the stakeholders, shown by the sudden increases in annual value. They are careful to maintain an annual value that satisfies the stakeholders, resulting in a ten-year LCV score of 11.21 against a desired value of 10. Manufacturer B is less likely to change their current plans unless the SC (SoS) itself changes.

7. SoS Dynamic Optimization

The preceding sections lay the groundwork to define ***dynamic optimization*** in the context of SoS, the primary concept of this work, as *the continuing development of an uncontrolled SoS through the dynamic interaction of all stakeholders, each attempting to achieve their own perceived local optimization of the SoS.* Dynamic optimization of a SoS occurs through the observed complexity behaviors of emergence, local information, intelligent agents, self-organization and adaptation, influenced by shared values among the stakeholders. It should be noted that the use of the term “optimization” refers to the perception of each stakeholder, seeking the optimum for their own value measurement. There is in fact no true optimum for the SoS, because there is no agreement on the fitness measures.

7.1. Stakeholder Interaction

The examples in the previous section show how each stakeholder perceives value in the SoS, and how the stakeholders are thereby influenced to make changes in the portion of the SoS over which they have control. Table 4 shows two manufacturers scheduling such changes based on their perceptions of value. These decisions, however, are not made in a vacuum; they are always made within the dynamics of the higher-level, uncontrolled SoS.

As each stakeholder makes a change in the SoS network, that change affects other stakeholders. This is part of the recursive nature of the SoS, in that the changes implemented locally feed back to the source through many other seemingly-local interactions that in fact cause global changes in the SoS. In the example of Table 4, the major change made by manufacturer A in 2008 causes reactive adjustments by the suppliers. Some suppliers connect more fully with manufacturer A and thereby reduce their capacity to support manufacturer B. This causes perturbation in the projections used by B for planning, and the actual value of the SoS to B in 2008/09 becomes something less than the projected values of 1.18 and 1.12. In subsequent years, therefore, B may be more likely to implement a change earlier than planned, perhaps upgrading in 2009 rather than in 2011. There have been no direct communications between A and B, yet the interactions happen through the consequential chain of suppliers.

These types of interactions are documented in the SCM descriptions of Choi et al. (2001), even to the extent of recognizing that manufacturers have been literally unable to maintain a complete map of the supply network due to the dynamism of change. The interactions are not limited to stakeholders of the same class. All stakeholders in the SoS eventually find themselves responding to the actions of all other stakeholders. The “butterfly effect” documented in complexity theory (Hilborn 2004) becomes profound, as small perturbations at remote points cause existence-threatening reactions to seemingly-random SoS stakeholders.

7.2. Environmental Influences

To each stakeholder, this dynamism appears to be environmental in nature. SE is founded on the principle of a “system,” a collection of interacting components viewed in relation to function. In this principle, components are viewed as “part of the system,” while all other objects are viewed as the environment within which the system operates. In the value analysis of the preceding section, stakeholders usually view their own controllable elements as "the system" while the rest of the SoS is viewed as environment. But all systems are really connected, and any perceived boundary is only an artifact of analysis. An external observer may view the manufacturer's elements as "the system," or may view the entire SC as "the system," or may view the economy in which the SC exists as "the system." This difference in level of perception leads to many of the strange and surprising interactions seen in the behavior of complexity.

In any value analysis, the stakeholder evaluates the environment, attempting to forecast the possible changes therein. Stakeholder actions are predicated on the projected conditions of the environment. When the environment changes, the stakeholder's preferences also change. As new possibilities come to light, the stakeholder desires to incorporate them. This causes a change in the preferences as shown in the example numbers of Table 5, in which a change in the knowledge about what inventory levels are sufficient causes manufacturer C to change its preferred level of parts inventory. As the documented and projected numbers for an environmental parameter change, the stakeholder preferences for their own value changes. As a result, a system that does not change gradually loses value in the eyes of the stakeholders. This change in LCV due to the perception of the environment was also explored by Browning and Honour (2005).

The resulting behavior of the stakeholders is to implement local change. In the SC example, manufacturer C has increasing desire to improve its SCM systems and becomes more likely to make some change. Such a change happens, not in reaction to individual changes of the other SoS participants, but rather in reaction to the aggregate change in the SoS behavior. As a result of the change at manufacturer C, the SoS itself changes even more.

Table 5 Stakeholder preferences change with the environment.

Year	**Industry Avg Parts Inventory Cost** (% of Sales)	**Manufacturer C Preferences** (Worst/Mode/Best)	**Utility of a System with Inventory at 7.5%**
2005	8.3%	10 / 8.1 / 5	1.19
2006	7.9%	10 / 7.5 / 4	1.11
2007	7.7%	9.5 / 7.4 / 4	0.95
2008	7.5%	9.5 / 7.2 / 4	0.87

7.3. Optimization of the SoS

The previous paragraphs describe the nature of dynamic optimization, in which stakeholders react locally to external changes. Optimization is more difficult to describe. What is the meaning of optimization in terms of an uncontrolled SoS? Each stakeholder has a different value measure based on different key parameters. Even stakeholders of the same class have different preferences and weights for the key parameters, and may also have different parameters. Is there any measure for optimization of the SoS as a whole?

By extension of the thoughts of Browning and Honour (2005), the aggregate value of the SoS to the set of stakeholders may be measured by a mathematical combination of the value to each stakeholder. The difficulty is in the definition of the combination (i.e. the weights in a weighted sum, if used). In the previous work, weights could be perceived by the system owner. For an uncontrolled SoS, however, there is no system owner. Because any value proposition is viewed from the viewpoint of a person, however, the SoS *observer* must decide on the values that matter. Several logical sets of weights may be chosen; for example, weights may be assigned:

- Equally to all stakeholders, or
- Proportional to the stakeholder “size” within the SoS (by some measure of size), or
- Proportional to the stakeholder financial contribution to the SoS, or others.

Regardless of the weights given to individual stakeholders, and regardless of the mathematical combinatorial method used, it is important to note that the KPs used by the stakeholders themselves fall in two categories: shared KPs and unshared or conflicting KPs.

Shared KPs are those in which there is a strong positive correlation among a significant number of stakeholders. In the SCM example, “parts lead time” for a manufacturer is strongly correlated with “responsiveness” for a supplier. Preferred improvement in one is enhanced by preferred improvement in the other. In this case, therefore, any action by a supplier to improve responsiveness will also increase the value of the SoS to the manufacturer and vice-versa. It can also be argued that this correlation extends to other suppliers and to other manufacturers, that a general increase in the value of the overall SoS occurs when these shared KPs are improved by any participant.

Conflicting KPs are those in which there is a strong negative correlation among stakeholders. “Transported tonnage” by one transporter takes away from “transported tonnage” by another. As each stakeholder seeks to improve its unshared KPs, they decrease the value of the SoS to other stakeholders.

Yet these conditions are exactly those determined by complexity theory to enhance the growth of a CAS as noted earlier. In a SC, each stakeholder has:

- Positive feedback in the form of the shared KPs,
- Negative feedback in the form of the conflicting KPs,
- A balance of exploration and exploitation caused by the dynamics of the stakeholder interactions, and
- A plethora of interactions driven by each stakeholder’s desire to optimize its own situation.

Each change created by a stakeholder results in some movement of the SoS value along the dimensions of shared and conflicting KPs. Figure 4 shows the SoS value as perceived by Manufacturer C during a series of uncontrolled changes. Change #1, implemented by Manufacturer C itself, improves both its shared and conflicting KPs. The next change, by Supplier 4, causes a reduction in the conflicting KPs as viewed by C. (Of course, this change likely caused an increase in the KPs important to Supplier 4.) Each successive change by other stakeholders results in a value change for Manufacturer C. While the movement along conflicting KPs becomes a “random walk” due to the differing desires of the stakeholders, movement along the shared KPs is reinforced by each stakeholder. Hence, all stakeholders pursue improvement in the directions that lead to greater connectivity, more detailed functionality, and reduced costs and risks, which are all shared KPs in the SC.

This description assumes that the actions of the stakeholders in this uncontrolled SoS are independent. Each stakeholder changes the SC in response to their own perceptions of value. The actions become reflexive (in the complexity sense) on other stakeholders, with each action causing what appears to be a change in the “environment” of the other stakeholders. Yet in some cases, these actions may not be independent. Stakeholders may form federations that agree on the types and timing of changes. Some stakeholders, such as tool vendors like SAP, might have such pervasive effect as to cause many other stakeholders to take similar actions. The relative size and power of the stakeholders may affect the interactions. Powerful nodes in the supplier network (e.g., Wal-Mart or Dell) are able to push more risk onto other, less-powerful nodes. Thus, the amount of power asymmetry in the network may determine the extent to which benefits are shared.

Also, one may question the potential effects of dramatic environmental changes that cause the addition of significant, new KPs or major, step-function changes in KPs or their relative weightings. For example, as the nodes (companies) in supplier networks become more specialized, they become more dependent on the network as a whole for reaping the benefits of their function. As companies reduce their inventories, they become less buffered and potentially less resilient in the face of SC disruptions. Indeed, the important KPs relating to various kinds of risk are often downplayed in many SoSs until catastrophic events reveal a set of underlying problems. Thus, depending on how the KPs are formulated and combined, even actions which appear to benefit the entire SoS could portend significant risks.

It should be noted, however, that many of these arguments are qualitative in nature, and all are not yet supported by formal analysis or empirical research. Further work is needed to expand these observations with a rigor that can support detailed analysis of the SoS dynamic optimization. Therefore, we view this framework as a platform for research rather than a finished product.

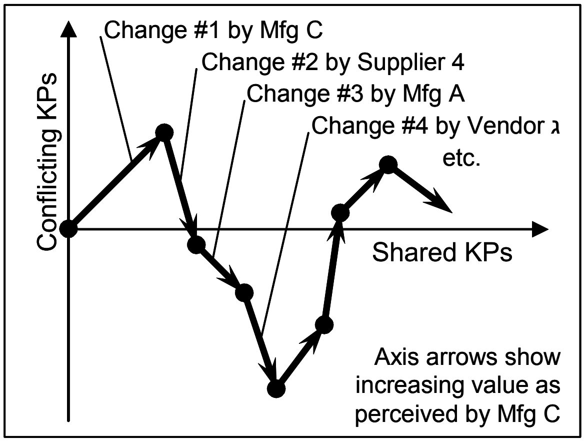

Fig. 4 SoS dynamic optimization by individual stakeholder actions.

8. Conclusions

SoSs have come into being in recent years in response to the inexpensive availability of networked computing, resulting in a technology nexus, the Networking Revolution, that appears to be as significant as the Industrial Revolution and the Computing Revolution. SE is only now beginning to understand the implications of SoSs on the tried-and-true methods of system development. Of particular difficulty is the uncontrolled SoS, with no owner, the development for which occurs as a result of individual actions by many stakeholders. In this work, we have shown how *dynamic optimization* describes the growth of such a SoS.

These concepts are based in complexity theory, which describes CASs as those with intelligent agents operating on local information to self-organize based on local optimization of both shared and conflicting values. Complexity theory has for many years explored the observed behavior of complexity in the areas of economics, physics, and biology, but has not yet had an impact on the engineering of complex systems and SoSs. SE has been a pragmatic, multi-disciplinary field offering empirical solutions to the development of engineered systems. Only very recently have these two fields started to interact, with the realization that SE is and always has been the engineering of complexity.

Recent SE work has moved toward quantification of value propositions as a basis for proof of the SE principles and methods. This proof has led to the beginnings of an understanding of the value of SE and the LCV of a system. Through extension of these thoughts, this work shows how the value of a SoS is perceived by its many stakeholders, and how these stakeholders modify the SoS in response to their perceptions. The result is the behavior that we have called *dynamic optimization*, in which the many stakeholder interactions cause a generally ongoing movement of the SoS value in the direction of the shared values of the stakeholders, albeit with many tangents caused by the conflicting values.

Further work is indicated in understanding more about the value propositions of stakeholders in a SoS. In what way do stakeholders perceive value, and how does that value change over time? How do changes in the stakeholders, the systems, and the SoS modify the perceived value? How do federations and agreements among the SoS stakeholders affect the dynamic optimization, and in what ways do they control or undermine the desirable actions of the SoS? Further work is also indicated in the mathematics of the final proposition of this work, that random movement by the stakeholders results in advancement of the SoS in the direction of shared values.

9. References

Arrow K.J., 1951, Social Choice and Individual Values, Wiley, New York.

Boardman, J., Fairbairn, A., Wilson, M., 2005, “Addressing the System of Systems Challenge,” Proceedings of the 15th Annual International Symposium of INCOSE, Rochester, NY.

Browning T.R., 1998, Modeling and Analyzing Cost, Schedule, and Performance in Complex System Product Development, Ph.D. Thesis (TMP), Massachusetts Institute of Technology, Cambridge, MA.

Browning T.R., 2003, "On Customer Value and Improvement in Product Development Processes," Systems Engineering, Vol. 8, No.1, pp. 49-61.

Browning T.R, and Honour, E.C., 2005, “Measuring the Life Cycle Value of a System,” Proceedings of the 15th Annual International Symposium of INCOSE, Rochester, NY.

Choi T.Y., Dooley, K.J., and Rungtusanatham, M., 2001, “Supply Networks and Complex Adaptive Systems: Control Versus Emergence,” Journal of Operations Management, vol.19, pp.351-366.

Cook H.E., 1997, Product Management: Value, Quality, Cost, Price, Profits, and Organization, Kluwer (was Chapman & Hall), New York.

Cook H.E. and Wu, A., 2001, "On the Valuation of Goods and Selection of the Best Design Alternative," Research In Engineering Design, Vol. 13, No. 1, pp. 42-54.

Darwin, C., 1859, On the Origin of Species by Means of Natural Selection, London.

DoD (Director, Systems and Software Engineering; Deputy Undersecretary of Defense, Acquisition and Technology), 2006, Systems of Systems Systems Engineering Guide: Considerations for Systems Engineering in a Systems of Systems Environment, Washington, DC, dated 22 Dec 2006

DoD, 2007, DoD Architecture Framework, Version 1.50, U.S. Dept. of Defense, DoD Architecture Framework Working Group, dated 23 Apr 2007.

Gilb, T., 2004, "Software Project Management: Adding Stakeholder Metrics to Agile Projects," Proceedings of the 14th Annual International Symposium of INCOSE, Toulouse, France.

Goode, H.H. and Machol, R.E.. 1957, System Engineering: An Introduction to the Design of Large-Scale Systems, McGraw-Hill, New York.

Grisogono, A.M. and Ryan, A., 2005, “Complex Adaptive Systems,” Proceedings of the Systems Engineering, Test and Evaluation Conference, Brisbane, Queensland.

Hilborn, R.C., 2004, “"Sea gulls, butterflies, and grasshoppers: A brief history of the butterfly effect in nonlinear dynamics," American Journal of Physics, Vol. 72, pp. 425–427.

Hofstadter, D., 1979, Gödel, Escher and Bach: An Eternal Golden Braid, Basic Books.

Honour, E.C., 1999, “Characteristics of Engineering Disciplines,” Proceedings of the 13th International Conference on Systems Engineering (ICSE99), Las Vegas, NV.

Honour E.C., 2001, "Optimising the Value of Systems Engineering," Proceedings of the 11th Annual International Symposium of INCOSE, Melbourne, Australia.

Honour, E.C., 2004, “Understanding the Value of Systems Engineering,” Proceedings of the 14th Annual International Symposium of INCOSE, Toulouse, France.

Honour, E.C. and Valerdi, R., 2006, “Advancing an Ontology for Systems Engineering to Allow Consistent Measurement,” Proceedings of the Conference on Systems Engineering Research, Los Angeles, CA.

INCOSE, 2006, Systems Engineering Handbook, version 3, Seattle, WA.

Keeney R.L. and Raiffa, H., 1976, Decisions with Multiple Objectives: Preferences, and Value Tradeoff, Wiley, New York.

Levis, A., Maier, M., Sage, A., 2004, “Academic Audit of AFIT Programs in Systems Engineering,” USAF Report SAB TR-05-04, US Air Force, Washington, DC.

Maier, M., 2007, “Architecting Principles for Systems-of-Systems,” http://www.infoed.com/Open/PAPERS/systems.htm (cited 10 Jun 2007).

Ravichandar, R., Arthur, J.D., and Bohner, S.A., 2007, “Capabilities Engineering: Constructing Change-Tolerant Systems,” Proceedings of the 40th Annual Hawaii International Conference on Systems Sciences, IEEE Computer Society, Waikaloa, HI.

Ring J., 2000, "Discovering the Value of Systems Engineering," Proceedings of the 10th Annual International Symposium of INCOSE, Minneapolis, pp. 271-278.

Saaty T., 1980, The Analytic Hierarchy Process, McGraw-Hill, New York.

Slywotsky A.J., 1996, Value Migration: How to Think Several Moves Ahead of the Competition, Harvard Business School Press, Boston.

Thomson D.S., Austin, S.A., Devine-Wright, H. and Mills, G.R., 2003a, "Managing Value and Quality in Design, "Building Research & Information, Vol. 31, No. 5, pp. 334-345.

Thomson D.S., Austin, S.A., Devine-Wright, H. and Mills, G.R., 2003b, "Addressing the Subjective View of Value Delivery," Proceedings of the Cobra '03 Conference, Telford, UK, pp. 197-213.

Von Neumann, J., 1966, The Theory of Self Reproducing Automata, (A. Burks, ed.), University of Illinois Press, Urbana, IL.

Wald, A., 1947, Sequential analysis. Wiley, New York.

Waldrop, M., 1992, Complexity: The Emerging Science at the Edge of Order and Chaos, Touchstone, New York.

Warmkessel J.M. and Slack, R.A., 1999 "Using Value to Define System Requirements," Proceedings of the 13th International Conference on Systems Engineering (ICSE99), Las Vegas, NV.

Wikipedia contributors, 2007, “Systems of Systems,” Wikipedia, The Free Encyclopedia, Wikimedia Foundation, http://en.wikipedia.org/wiki/System_of_systems (cited 10 Jun 2007).

Woodruff R.B. and Gardial, S.F., 1996, Know Your Customer: New Approaches to Understanding Customer Value and Satisfaction, Blackwell, Cambridge, MA.

10. Acronyms

ANSI	American National Standards Institute
CAS	Complex adaptive systems
CMMI	Capability Maturity Model Integration
DoD	Department of Defense
DODAF	Department of Defense Architecture Framework
EIA	Electronics Industry Association
IEEE	Institute of Electrical and Electronics Engineers
INCOSE	International Council on Systems Engineering
ISO	International Standards Organizations
JCIDS	Joint Capabilities Integration and Development System
JFCOM	Joint Forces Command
KP	Key parameter
LCV	Life-cycle value
LIB	Larger is better

MIL-STD	Military Standard
OPEC	Organization of Petroleum Exporting Countries
SC	Supply chain
SCM	Supply chain management
SE	Systems engineering
SIB	Smaller is better
SoS	System of systems
SoSE	Systems of systems engineering
VALiD	Value in Design

11. Authors' Biographies

Eric Honour was the 1997 INCOSE President. He has a BSSE from the U.S. Naval Academy and MSEE from the U.S. Naval Postgraduate School, with 38 years of systems experience. He is currently a doctoral candidate at the University of South Australia based on his research into the ROI of SE. He was a naval officer for nine years, using electronic systems in P-3 anti-submarine warfare aircraft. He has been a systems engineer, engineering manager, and program manager with Harris, E Systems, and Link. He has taught engineering at USNA, at community colleges, and in continuing education courses. He was the founding President of the Space Coast Chapter of INCOSE, the founding chair of the INCOSE Technical Board, and past director of the Systems Engineering Center of Excellence. He was selected in 2000 for Who's Who in Science and Technology and in 2004 as an INCOSE Founder, and serves on the editorial board of *Systems Engineering*. Mr. Honour provides technical management support and systems engineering training as President of Honourcode, Inc., while continuing research into the quantification of systems engineering.

Dr. Tyson R. Browning is Assistant Professor of Enterprise Operations at the Neeley School of Business, Texas Christian University in Fort Worth, Texas. He teaches Operations Management and Program Management in the MBA program and conducts research on enterprise operations, process modeling, product development, project management, and systems engineering. Prior to joining TCU, he was a Senior Project Manager at Lockheed Martin Aeronautics Company and also worked for the Lean Aerospace Initiative, Honeywell Space Systems, and Los Alamos National Laboratory. He received a B.S. in Engineering Physics from Abilene Christian University and two Master's degrees and a Ph.D. from M.I.T. He is a member of INCOSE, INFORMS, and POMS and serves on the editorial board of the journal *Systems Engineering*.