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Designing Resilient, Sustainable Systems

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Pursuit of sustainable development requires a systems approach to the design of industrial product and service systems. Although many business enterprises have adopted sustainability goals, the actual development of sustainable systems remains challenging because of the broad range of economic, environmental and social factors that need to be considered across the system life cycle. Traditional systems engineering practices try to anticipate and resist disruptions but may be vulnerable to unforeseen factors. An alternative is to design systems with inherent "resilience" by taking advantage of fundamental properties such as diversity, efficiency, adaptability, and cohesion. Previous work on sustainable design has focused largely upon ecological efficiency improvements. For example, companies have found that reducing material and energy intensity and converting wastes into valuable secondary products creates value for shareholders as well as for society at large. To encourage broader systems thinking, a design protocol is presented that involves the following steps: identifying system function and boundaries, establishing requirements, selecting appropriate technologies, developing a system design, evaluating anticipated performance, and devising a practical means for system deployment. The approach encourages explicit consideration of resilience in both engineered systems and the larger systems in which they are embedded.

> *Connected, distributed systems, from power grids to business firms to even entire economies, are both more fragile and more robust than populations of isolated entities.*
>
> Duncan J. Watts (*1*)

Overview

We live in a small world of ever-increasing connectivity, with both cooperation and conflict occurring on a global scale. Individuals, companies, and communities are linked through worldwide systems of communication, transportation, and commerce. Similarly, individual products and services are linked to the global value chains in which they are created, delivered, and used. This connectivity presents daunting challenges to the design and commercialization of new systems. Instead of focusing purely on the function and form of a product or service, design teams today must consider a broad range of system-level issues, including safety, security, manufacturability, serviceability, material and energy efficiency, end-of-life recovery, environmental emissions, and even long-term impacts upon quality of life for future generations (*2*).

In the face of such complexity, traditional methods for analyzing costs, benefits, and risks can become overwhelming. Instead, it is helpful to delve more deeply into the fundamental properties of successful systems in the biological, social, and commercial arenas. What do such systems have in common? They are complex, adaptive, and unpredictable. They exhibit self-organizing behavior that enables continuity in response to external stress. They can survive unexpected disruptions, although they can also fail catastrophically. Likewise, engineered systems cannot be designed to anticipate all future possibilities, as evidenced most recently by the *Columbia* shuttle disaster and the Northeast electrical power blackout of 2003. Nevertheless, engineered systems can be endowed with intrinsic characteristics that improve their robustness and adaptability.

This paper considers how an industrial enterprise can work toward sustainability by adopting a fresh perspective based on systems thinking. The concept of "resilience", borrowed from the field of ecology, enables sustainability to be viewed as an inherent system property rather than an abstract goal. Already, existing design practices have demonstrated many useful techniques for enhancing system resilience. Building on these insights, a generalized approach to sustainable systems design is presented, including explicit consideration of system boundary conditions and external impacts.

Toward Sustainable Systems

In industries ranging from resource extraction (e.g., petroleum, lumber) to conversion and processing (e.g., chemicals, electric power) to consumer goods (e.g., packaged foods, electronics), shareholders and analysts have become sensitized to a company's ecological and social "footprint", including global issues such as climate change and poverty. Many leading corporations have adopted the concept of sustainable development (*3*), recognizing that environmental protection and social responsibility are important to both shareholders and other stakeholders (*4*). Yet, despite their heightened awareness and commitment, most companies have found it difficult to translate broad goals and policies into day-to-day decision-making.

There are several barriers that limit the practical application of sustainable development principles. For one thing, the notion of protecting future generations seems remote in the face of contemporary business pressures. The concept of "sustainability" is often associated with resource constraints and maintenance of status quo rather than with opportunities for continued innovation, growth, and prosperity. In addition, the popular metaphor of the "triple bottom line" (*5*) seems to imply that economic profits need to be "balanced" against environmental and social benefits, whereas in truth these three aspects of corporate performance are inseparable and contribute synergistically to shareholder value (*6*). Finally, sustainability is often misinterpreted as a *goal* to which we should collectively aspire. In fact, sustainability is not an end state that we can reach; rather, it is a *characteristic* of a dynamic, evolving system. And systems thinking offers a potential means to overcome the above barriers.

Alternative definitions of sustainability abound, but for system design purposes the following definition is useful: A product, process, or service contributes to sustainability if it constrains environmental resource consumption and waste generation to an acceptable (*7*) level, supports the satisfaction of important human needs, and provides enduring economic value to the business enterprise (*8*). Note that a product cannot be sustainable in an absolute sense; rather, it must be considered in the context of the supply chain, the market,

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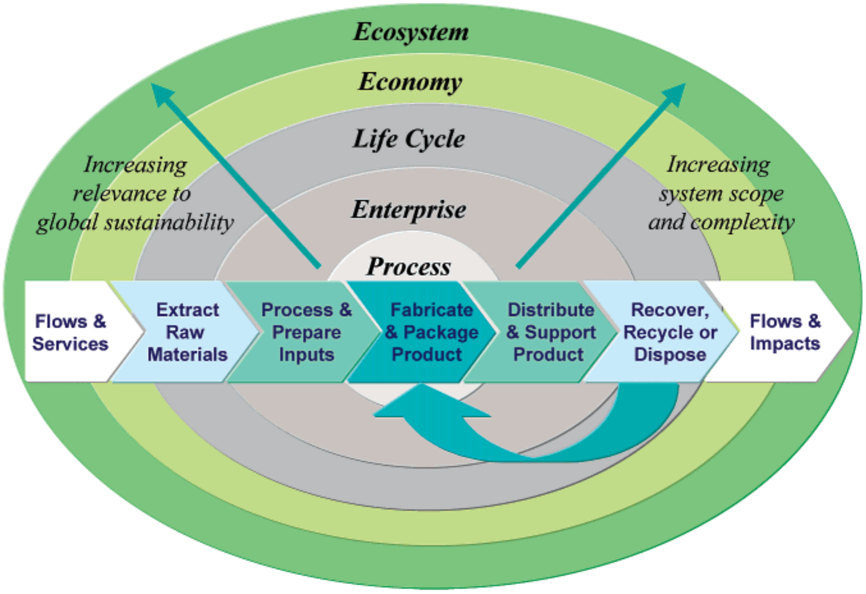

FIGURE 1. Extending the boundaries of system design (*8*).

and the natural environment. Therefore, the key practical challenge of sustainable design is to understand how products, processes, and services interact with these broader systems. As illustrated in Figure 1, full exploration of this question would extend beyond the enterprise, even beyond the conventional "product life cycle", to the underlying economic flows as well as ecosystem services derived from "natural capital" (*9*). How, then, does one establish realistic boundaries for system design?

The challenge of boundary definition is evident in a "sustainable mobility" study being conducted by an international group of automotive and energy companies working with the World Business Council for Sustainable Development. Their goal is for humans to "move freely, gain access, communicate, trade and establish relationships without sacrificing other essential human or ecological values, today or in the future" (*10*). A key issue is how future transportation technologies and demand patterns will evolve, together with their supporting infrastructures (e.g., adoption of hydrogen fuel cells for automotive vehicles will require development of a new refueling network). The infrastructure question is especially challenging since it encompasses roads, railways, airports, intermodal freight terminals, and maintenance and guidance systems. Ultimately, the evolution of mobility systems will be influenced by urban and regional planning policies as well as competing supply chain management strategies. The vast scope of these interlocking systems is bewildering for any business enterprise seeking to develop a sustainable business strategy for mobility-related products and services.

What Is a Sustainable Enterprise?

During the 1990s, Royal Dutch Shell conducted a historical study of corporations in an effort to understand what drives corporate longevity (*11*). They found that the average life expectancy of large corporations worldwide was less than 50 years—in effect, most companies die prematurely. Furthermore, they identified four factors that distinguished long-lived companies:

(i) sensitivity and adaptability to the business environment
(ii) cohesion and sense of identity
(iii) tolerance of diversity (decentralization)
(iv) conservative use of capital

Profitability was conspicuously absent from this list and was considered to be an outcome rather than a predictor of longevity—many companies have delivered spectacular profits for short periods of time and then vanished abruptly. From this study emerged the notion that the real purpose of a corporation is to learn, grow, and survive in the long run and that a corporation is best understood as a living organism rather than as a machine engineered to deliver profits. More recently, a decade-long study of 160 companies indicated that the main determinants of superior financial performance were not technology-based but rather were organic system traits—an achievement-oriented culture, a flexible and responsive structure, a clear and focused strategy, and flawless execution (*12*). Moreover, the enterprise system needs to encourage recognition that the future may not resemble the past since individuals often tend to cling to the familiar status quo (*13*).

This organic view of the corporation is consistent with an emerging recognition by the business community of "intangible" value drivers. Company characteristics such as human capital, innovation, alliances, and brand equity are increasingly viewed as leading indicators of shareholder value (*14*). Moreover, paying attention to social and environmental performance strengthens many of these intangibles, including reputation, stakeholder relationships, employee pride, efficient technology, and license to operate. In short, an enterprise that contributes to sustainable development enhances its own sustainability as a business. Unfortunately, the term sustainability has become both ambiguous and laden with ethical connotations. The following definitions offer a logical framework of "nested" systems that may be helpful to system designers.

(i) A sustainable society is one that continues to satisfy the current needs of its population without compromising quality of life for future generations.

(ii) A sustainable enterprise is one that continues to grow and adapt in order to meet the needs and expectations of its shareholders and stakeholders. (The enterprise system is a component of the overall socio-economic system.)

(iii) A sustainable product (or service) is one that continues, possibly with design modifications, to meet the needs of its producers, distributors, and customers. (The product system is a component of the overall enterprise system.)

The above definitions imply that social responsibility is a characteristic of the enterprise, not of the product or service, and requires continuous adaptation to ensure transparency and responsiveness to the changing needs of stakeholders. Ecological integrity and quality of life, however, are often influenced by characteristics of a product or service and thus can be addressed through sustainable design principles. Finally, sustainable development, in the sense of addressing the needs of future generations, can only be addressed meaningfully at the level of a collective society. Individual products or enterprises cannot be deemed sustainable in isolation, although they can make important contributions to the fulfillment of specific human needs. Nor can corporations alone be held accountable for sustainable development—supply and demand are coupled. Achieving a sustainable society will require cooperative efforts among industry, government, and public interest groups to ensure not only sustainable production systems but also sustainable consumption patterns on the part of individuals and institutions (*15*).

In effect, product/service systems are the offspring of corporations and acquire important characteristics from their "parents" including branding, technology, distribution channels, and stakeholder perception. Today, corporations are increasingly expected to disclose the origins of products, including raw materials, and the conditions under which they were manufactured. Do they employ forced labor or child labor? Do they utilize recycled material content or renewable energy? Were chlorofluorocarbons (CFCs) used in the manufacturing process? Do they contain genetically engineered constituents? As we broaden the scope of product/service design, we inevitably begin to consider the higher-order characteristics of the systems in which they are embedded.

Resilience and Sustainability

Systems theory is the study of how complex entities interact openly with their environments and evolve continually by acquiring new, "emergent" properties (*16*). Rather than reducing an entity (e.g., the human body) to the properties of its parts or elements (e.g., organs or cells), systems theory focuses on the relationships (e.g., feedback loops) between the parts that connect them into a whole. It turns out that many system properties are independent of the concrete substance of their elements (e.g. particles, cells, transistors, people). Complex systems are generally dynamic, nonlinear, and capable of self-organization to sustain their existence. For example, by pollinating flowers, bees create a feedback loop that reinforces the production of nectar. Similarly, by supporting social and philanthropic activities, corporations strengthen the vitality of the communities to which their employees belong.

By the laws of thermodynamics, closed systems will gradually decay from order into chaos, tending toward maximum entropy. However, living systems are "open" in the sense that they continually draw upon external sources of energy and maintain a stable state of low entropy that is far from thermodynamic equilibrium (*17*). Perhaps the essence of sustainability is *resilience*, the ability to resist disorder (*18*). Figure 2 provides a simplified illustration of thermodynamic changes that characterize different types of resilience. Each system has a stable state representing the lowest potential energy at which it maintains order, and each is subject to perturbations that shift it along a trajectory of adjacent states.

(i) System a is typical of engineered, highly controlled systems. It operates within a narrow band of possible states and is designed to resist perturbations from its equilibrium state. It recovers rapidly from small perturbations, but it may not survive a large perturbation. We call this a *resistant* system.

(ii) System b is typical of social and ecological systems. It can function across a broad spectrum of possible states and gradually tends to return to its equilibrium state. Through adaptation and evolution, it is capable of surviving large perturbations. We call this a *resilient* system.

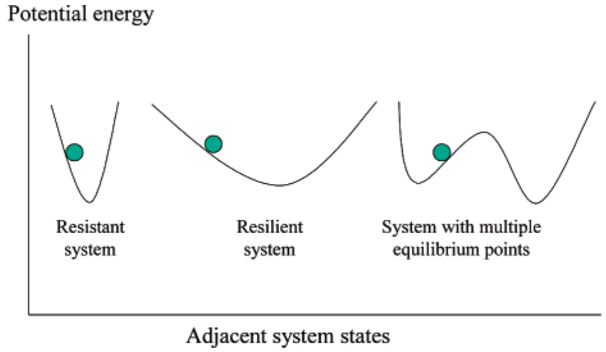

FIGURE 2. Examples of system behavior.

(iii) System c is even more resilient than system b in that it can tolerate larger perturbations. Under certain conditions it may shift to a different equilibrium state, representing a fundamental change in its structure and/or function.

The contrast between resistant and resilient systems is exemplified by China and India, both sophisticated civilizations that have flourished for centuries. Whereas China has tended to resist foreign influences and preserve homogeneity of language and religion, India has accepted and integrated foreign influences into a diverse tapestry of religious and cultural variants.

The concept of resilience and its applicability to ecological, social, and management systems has been investigated extensively by an international group of researchers led by two noted ecologists, Lance Gunderson and C. S. Holling. They have developed a general theory of adaptive cycles, arguing that all systems exhibit similar patterns of slow accumulation of resources, increasing connectedness, and decreasing resilience, punctuated by periods of crisis, transformation, and renewal (*19*). Based on an understanding of these patterns, humans may be able to intervene in appropriate ways that take advantage of the system dynamics rather than merely resisting change.

Applying Resilience to System Design

The design of engineered systems, including both hardware and software, has been approached traditionally as a process of hierarchical decomposition (i.e., the overall system function and architecture are developed first and then the systems and subsystems are designed accordingly). Complex, hierarchically organized systems (e.g., aircraft, nuclear plants) tend to have rigid operating parameters, are resistant to stress only within narrow boundaries, and may be vulnerable to small, unforeseen perturbations. Alternatively, distributed systems composed of independent yet interactive elements may deliver equivalent or better functionality with greater resilience. For example:

(i) A collection of distributed electric generators (e.g., fuel cells) connected to a power grid may be more reliable and fault-tolerant than a central power station.

(ii) A swarm of miniature unmanned surveillance drones may be less costly and more robust than a single conventional surveillance aircraft.

(iii) A network of autonomous software agents operating asynchronously may be more effective and speedier than a monolithic software program.

(iv) A geographically dispersed workforce linked by telecommunications may be less vulnerable to catastrophic events that could destroy a single facility.

While such distributed systems may not always represent a superior solution, they typify a novel approach to systems

TABLE 1. Characteristics of Resilient Systems

	diversity	efficiency	adaptability	cohesion
product system	multiple product configurations and extensions	value delivered relative to total cost of ownership	end-user product customization; failure recovery	strong brand identity; unique product features
enterprise system	encouragement of diverse business strategies	efficient decision processes; resource productivity	organizational learning; cash reserves	distinctive corporate culture; strong partnerships
ecosystem	biodiversity in terms of species variety	efficient ecological cycling of energy and nutrients	tolerance and assimilation of exogenous burdens	natural habitat boundaries; tightly clustered food web
socio-economic system	ethnic, cultural, institutional, and political diversity	cost-efficient means for human needs satisfaction	transparency and flexibility of major institutions	geographic boundaries; strong national identity

engineering, sometimes called “biomimicry”, that more closely resembles the patterns seen in living systems (*20*).

In addition to mimicking nature, system designers need to be aware of their impacts upon nature. It is often said that “nature is resilient”. Some argue that we should not impose unreasonable regulatory burdens upon industrial activities since we cannot predict their impacts upon complex ecosystems. Indeed, many regulatory restrictions are based on admittedly inadequate methodologies, such as the models used for extrapolating from laboratory studies to predict human cancer incidence due to chemical exposures. These models use “conservative” assumptions intended to overstate the true risk. In some cases, this precautionary approach may impose economic burdens that distort the economy. In other cases, the models fail to account for phenomena such as multi-pollutant synergies and may actually understate the risk. Similarly, the worldwide elimination of CFCs was undertaken without a clear understanding of the their impacts upon atmospheric ozone.

Scientists may never be able to predict accurately the impacts of perturbations upon biological or ecological systems. The emergent properties of open systems give them the capacity to tolerate perturbations and to evolve into new, unimagined forms. However, it is possible to explore the properties of both natural and engineered systems that make them more or less resilient. As shown in Table 1, there are several key characteristics of living systems that can also be extended to industrial systems. For example, it is commonly argued among ecologists that a decrease in biodiversity will tend to reduce ecosystem stability (*21*). As mentioned earlier, a similar observation was made in the Shell study of corporate longevity—a decrease in managerial diversity reduces a company’s ability to survive upheavals.

As a starting point for sustainable system design, Table 1 identifies four major system characteristics that contribute to resilience and interprets them in the context of the nested systems discussed earlier. These characteristics are as follows:

(i) Diversity—existence of multiple forms and behaviors;

(ii) Efficiency—performance with modest resource consumption;

(iii) Adaptability—flexibility to change in response to new pressures;

(iv) Cohesion—existence of unifying forces or linkages.

An understanding of system resilience becomes important when significant disruptions or discontinuities occur that shift the system away from its current equilibrium state. Such disruptions could include the introduction of new technologies, the emergence of new regulatory and market forces, or changes in the availability of resources. For example, will the broad introduction of low-cost electronic devices in developing nations create an excessive flow of post-consumer wastes, and how will local governments respond? Some believe that emerging sustainability issues will catalyze innovations that will change the basis of competition in many industries (*22*). Those that wish to reap the benefits of these changes must also be alert to the risks—complex systems may be vulnerable to small, unforeseen perturbations that cause catastrophic failures. Already, practitioners of enterprise risk management are beginning to adopt resilience concepts as a way to “withstand systemic discontinuities and adapt to new risk environments” (*23*).

There are numerous instances of system design practices that have contributed to sustainability improvements, especially with regard to ecological issues. For example:

(i) Sustainable Building Systems. Many architects and engineers have embraced the concepts of “green” or sustainable buildings. According to the U.S. Department of Energy, buildings consume about 33% of all the energy used in the United States and 66% of all electricity, thus accounting for about 35% of all carbon dioxide emissions (*24*). Examples of sustainable design practices include energy efficiency, use of local materials, respect for natural surroundings, utilization of ecological services (e.g., heating and cooling), and sensitivity to human well-being (*25*). Apart from the obvious energy and environmental benefits, studies suggest that sustainable buildings also improve employee satisfaction and productivity (*26*). The LEED protocol, developed by the U.S. Green Building Council, is widely used to evaluate environmental performance from a “whole building” perspective over a building’s life cycle. At a higher system level, a number of academic and research institutions, such as University of California at Berkeley, have developed plans and guidelines for sustainable campuses.

(ii) Sustainable Process Systems. Over the past decade, the field of process systems engineering has gradually expanded from a traditional focus on process technology and economics to incorporate sustainability issues such as process safety and environmental emissions (*27*). The synergy between process performance and sustainability is well captured in the concept of *eco-efficiency*, which measures the value produced as output per unit of resource input (*28*). Reductions in labor intensity, energy consumption, process hazards, and waste generation tend to translate into lower capital requirements, lower economic risks, and lower operating and maintenance costs. New technologies such as process intensification and microreactors have demonstrated the potential for order of magnitude increases in process yield and capital productivity. At the same time, significant advances have occurred in the field of green chemistry, also known as sustainable chemistry, which seeks new pathways and catalysts for environmentally benign chemical synthesis and processing (*29*). For example, Dow Chemical and other companies are using novel processing methods to convert renewable biomass (e.g., soybeans, corn, cellulose) into useful materials such as adhesives and plasticizers.

(iii) Sustainable Supply Chain Systems. Products such as automobiles and computers, which involve a series of discrete manufacturing and assembly processes along the supply chain, can generate a significant ecological footprint in terms of material, energy, and land use as well as industrial wastes and emissions. Manufacturers such as General Motors and HP have utilized a variety of “design for environment” techniques (*30*) to reduce the resource intensity of their manufacturing and logistical systems. These techniques include simplifying product architecture to reduce the number of distinct parts and assembly operations (which also enables easier maintenance and disassembly); utilizing recycled materials or refurbished components; avoiding substances with undesirable properties such as carcinogenicity, toxicity, flammability, ozone depletion, or environmental persistence; reducing electrical and thermal energy use through process modifications or transportation efficiency (e.g., improved product geometry for pallet loading); utilizing quality improvement and "lean" manufacturing techniques (e.g., just-in-time inventory replenishment) to reduce work-in-process and scrap; and collaborating with customers and suppliers to streamline the supply chain and minimize waste.

(iv) Sustainable Product Life Cycle Systems. Some companies have begun to look beyond the supply chain that they control and consider the full life cycles of their products and services, including resource extraction, procurement, transportation, manufacturing, product use, service, and end-of-life disposition or asset recovery (see Figure 1). For example, BASF Corp. has adopted a new eco-efficiency analysis tool to help identify products and processes that consume less energy and generate less waste than alternatives while maintaining or improving the products' commercial value (*31*). The tool has been applied to over 100 different products and processes such as asphalt microsurfacing, nylon fiber, building materials, automotive coatings, plastics, and adhesives. The resulting analyses have influenced BASF business decisions regarding capital investments, production techniques, acquisitions, and product positioning. BASF's methodology combines assessment of life cycle *ecological* impacts (including raw material and energy consumption, air and water emissions, and potential health risks) with an *economic* analysis of life cycle costs. Economic and ecological data are then plotted on a graph, revealing the eco-efficiency of a product or process as compared to competing products and processes.

(v) Sustainable Industrial Networks. Companies working in isolation may achieve incremental improvements in addressing sustainability issues; however, a more powerful approach is for companies to collectively optimize their activities as part of an *industrial ecology* network. Stated simply, industrial ecology is a framework for transforming industrial systems from a linear model to a closed-loop model that resembles the cyclical flows of ecosystems, in which one creature's waste becomes another creature's nutrients (*32*). Rather than exporting industrial and consumer wastes for disposition outside the system, industrial ecology suggests elimination of the very concept of waste by designing innovative pathways for conversion of wastes into useful byproducts. The scope of the "system" then encompasses all participating companies as well as the natural environment in which they operate. Simple examples are common: cement manufacturers incinerate contaminated wastes in cement kilns as a substitute for fossil fuel, effectively reducing global warming emissions; electric utilities recycle fly ash from their boilers for blending into cement and capture waste heat for local applications; electronic equipment recyclers recover parts and materials from discarded devices and recycle them into a variety of secondary uses. A more advanced example of industrial ecology is a complex at Kalundborg, Denmark, where "symbiotic" relationships have developed among several large facilities and a host of smaller ones. The main partners are a coal-fired power plant, a refinery, a plasterboard factory, and a pharmaceutical and enzyme plant operated by Novo Nordisk (*33*).

The main focus of the above design efforts has been upon a particular system characteristic—ecological efficiency. It is likely that companies will discover additional opportunities for value creation by expanding their scope to include other dimensions of Table 1 (i.e., finding ways to enhance the diversity, adaptability, and cohesion of engineered systems and the related systems with which they interact).

A Generalized Approach to Sustainable System Design

Among the vast range of systems that we encounter, there are many well-bounded systems that are truly "designed". Clothing, appliances, aircraft, and buildings, for example, are designed and then manufactured or assembled through a rigorously controlled series of processes. On the other hand, we participate in social and ecological systems that are not at all designed; yet we can still design policies and interventions that influence the system behavior and evolution. The latter case typifies virtually all of our environmental protection efforts—we introduce changes such as soil remediation, pollution reduction, reforestation, or streamflow diversion in an effort to enhance the health of the overall ecosystem.

Controlled design is the dominant focus of the product and process development community, and companies have made huge investments in design technology in order to improve the creativity, quality, and speed of system development. For example, the system acquisition processes utilized by the U.S. Department of Defense (DoD) engage dozens of organizations in a controlled design effort that encompasses the full life cycle of military systems. Inevitably, such efforts turn out to have unforeseen, inadvertent impacts upon related systems. For example, the DoD is currently examining the sustainability of domestic artillery test ranges in terms of their impacts upon surrounding communities, an issue that was overlooked for many years.

The unforeseen secondary impacts of system design may be trivial or profound. For example, in the case of automotive design:

(i) A structural design change that improves vehicle performance may have virtually no significant secondary impacts;

(ii) A change in the materials of construction may have substantial impacts on economic and ecological systems within the manufacturer's supply chain;

(iii) A new engine design may have not only supply chain impacts but also economic, environmental and social impacts that affect entire markets.

Thus, certain design decisions may constitute interventions in broader systems. From this perspective, "green engineering" and "design for environment" are efforts to anticipate and consider broader ecological system impacts within a controlled design process. More generally, "design for sustainability" represents an effort to consider both environmental and socio-economic systems. We cannot design a perfect natural environment or an ideal society, but we can try to modify the controllable characteristics of our designed artifacts (e.g., factories, products) in ways that create environmental and social benefits. Individual companies, especially market leaders, can exert powerful influences through such system interventions. Regulatory agencies can also exert powerful influences, but a more promising approach is collaborative partnerships whereby industry, government, and other interested parties jointly design interventions for the benefit of society. Without such partnerships, well-intentioned efforts may go awry; for example, airborne emissions might merely be shifted to waterborne effluents elsewhere in the supply chain, or the distribution of risks and benefits among workers and consumers might be inequitable. Perhaps the most ambitious example of collective system intervention is the worldwide effort to reduce greenhouse gas emissions.

To encourage systems design that incorporates sustainability thinking explicitly, it is useful to have a systematic

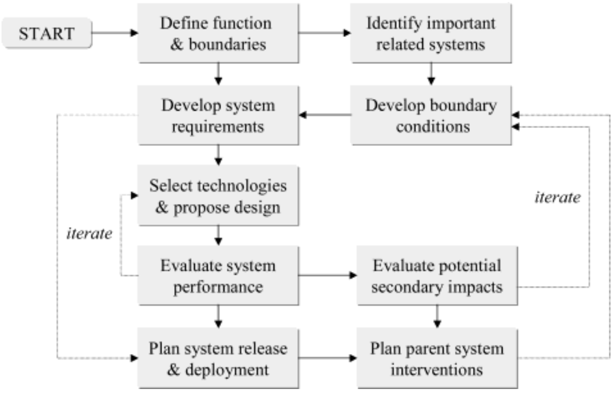

FIGURE 3. Expanded design protocol including system considerations.

protocol. Consideration of related (parent or sibling) systems and their resilience can be accomplished through an expansion of existing design protocols, as illustrated in Figure 3. At one extreme, if there are no important interactions anticipated with related systems, the protocol reduces to a standard "stage-gate" development process, commonly used in industry. At the other extreme, the external interactions may be so significant that the majority of the design effort is spent trying to understand related systems, including impacts and boundary constraints. Each of the steps in Figure 3 is described below.

Defining System Function and Boundaries

The sustainable mobility problem mentioned at the beginning of this paper illustrates the difficulty of establishing the scope for a system design effort. Every open system interacts with its environment and, hence, is part of a larger system. Carried to the extreme, this type of reasoning leads to the "Gaia hypothesis", which claims that the world is a single giant organism (*34*). This is not a very helpful perspective if one is trying to design an electronic appliance. However, a more practical application of systems thinking is to consider the related systems in which a design artifact is embedded—literally thinking outside the box. This may lead to surprising innovations. For example, the development of a telephone-answering device might be seen from several alternative related system perspectives:

(i) It is part of a home system from the *consumer use* perspective and can become a network appliance as well a communication device.

(ii) It is part of a material flow system from a *supply chain* perspective and can become a source of reusable components at end-of-life.

(iii) It is an enabling technology from a *developing economy* perspective and can serve as an element of an entrepreneurial communication service business.

It follows that one of the most important steps in system design is establishing a clear, practical definition of the *function* and *boundaries* of "the system". For example, are we creating a voice recording device, a telephone-answering system, or a voice mail service? Are we designing a physical device, a human interface, or a total solution delivery system? Depending on the system scope, the design methodology and technological options can vary greatly. A common way to define systems, for purposes of customer value analysis and life cycle analysis of competing designs, is in terms of a unit of functional value. In the above example, the functional unit chosen might be a "message capture event" including both recording and playback. Then alternative designs could be analyzed in terms of cost, reliability, ease of use, and resource efficiency per message capture event.

A good illustration of how system boundaries become broadened is in the field of industrial carpeting, which surprisingly has become a hotbed of sustainable design. Collins & Aikman Floorcoverings (now part of Tandus Group) has developed a closed-loop recovery process whereby customers return their carpet with assurance that 100% of it will be recycled into new carpet. Another industry leader, Interface, has pledged to offset the greenhouse gas (GHG) emissions from its floorcovering products with investments in GHG reduction projects such as installing energy-efficient boilers and lighting in public schools or planting trees that absorb greenhouse gases.

Developing System Requirements

In systems engineering, requirements definition and management has traditionally focused on observable product characteristics such as cost, structure (e.g., size, geometry), and functional performance. A *requirement* can be defined as a set of testable conditions applicable to products or processes (*35*). The conditions may be represented in various forms, ranging from qualitative statements (e.g., "system shall shut down when left idle") to quantitative metrics (e.g., power rating). Testing of requirements typically involves some human interpretation, and the broader the scope of the system, the more difficult it becomes to apply definitive tests. The requirements management process generally consists of three main functions that are performed in an iterative fashion:

(i) **Requirements analysis** involves interpreting customer needs and deriving explicit, verifiable requirements.

(ii) **Requirements tracking** involves analysis of design tradeoffs, including project risk, schedule, cost constraints, and performance goals. A *traceability* hierarchy is frequently used to keep track of changes in system and subsystem requirements.

(iii) **Requirements verification** involves determining whether a system design will meet the specified requirements. The earlier verification can be performed, the more likely it is that gaps or flaws will be detected before a large investment is made.

To incorporate sustainability issues, as shown in Figure 3, system requirements definition should take into account the boundary conditions derived from related systems. This may require thinking beyond the usual supply chain considerations to consider the broader industrial and social context. For example, recent European Union directives are requiring both electronics and automotive manufacturers to take responsibility for end-of-life vehicle recovery, stimulating reconsideration of the design assumptions for systems and their components. Another recent trend is the interest of multi-national companies such as Dow, HP, and Procter & Gamble in addressing the large, heretofore untapped markets at the bottom of the economic pyramid (*36*). They have found that designing products as well as marketing and distribution systems to serve low-income populations in developing nations requires a deep understanding of local conditions, resources, and behavior patterns. For example, in India, consumables such as detergent can now be purchased in one-cent single-serving pouches made of biodegradable plastic.

The life cycle issues that need to be emphasized in requirements definition vary greatly across different industries. Natural resource extraction industries such as mining, oil production, agriculture, and forest products might emphasize appropriate land use, ecosystem protection, and worker safety. Industries farther downstream in the supply chain such as petroleum refining, metals, chemicals, and electric utilities might emphasize process safety, conversion efficiency, and waste minimization. Industries close to the end-customer such as food and beverage, pharmaceuticals,

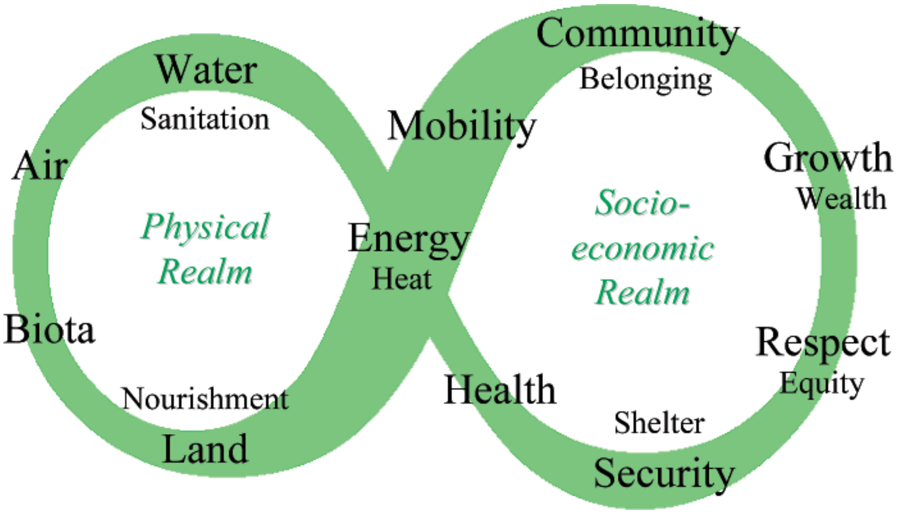

FIGURE 4. present and future human needs.

automotive, and electronics might emphasize environmentally conscious packaging (for consumable products), end-of-life recovery (for durable products), and responsiveness to social needs. Finally, service industries such as transportation, communication, and retailing might emphasize efficient logistics, product certification (e.g., lumber), and human resource development.

To develop sustainability requirements, it is helpful to consider a "mental map" of human needs, presented in Figure 4. Basic survival needs are associated with the physical realm, while higher-order needs are associated with the socio-economic realm. These two realms are closely intertwined, with energy needs playing a pivotal role—in fact, energy is the one essential input for all living systems. The current status of these needs, including significant gaps, may provide boundary conditions for system design; for example, in a region with severe water shortages, industrial depletion of water should be avoided. Practically speaking, the needs of society must be clarified and prioritized through *stakeholder engagement*, including a dialogue among corporations, government policy-makers, and public interest groups. Thus, there is no universal set of performance conditions that defines sustainability, even within a particular industry.

This ambiguity may be perplexing to a system designer accustomed to having performance-based requirements. For example, one might intuitively believe that a "zero-emission" factory was a worthwhile goal. Yet the technologies required to reduce plant emissions to zero might be both complex and costly. Instead, a combination of throughput reduction and partial conversion of wastes to useful byproducts might result in a superior environmental profile for the larger economic system in which the plant operates. Furthermore, a business strategy that encourages diversity in adjacent industrial development might create additional markets for waste materials.

Selecting Technologies and Creating a Design

Recent innovations in genomics, materials science, nanosystems, and information technology can contribute directly to sustainability by increasing the efficiency and adaptability of existing products and processes. For example, increased use of electronic communication and information storage may reduce the need for physical transportation and record-keeping, although we have yet to achieve a "paperless office". DuPont, for one, encourages its businesses to substitute intellectual capital for physical capital by measuring product performance in terms of shareholder value per pound of product sold.

However, there are hidden tradeoffs to consider. Systems that are smaller, faster, cheaper, and more flexible may actually have a larger environmental footprint than their bulkier, slower predecessors. In the semiconductor industry, for example, the precision manufacture of a tiny microchip consumes large amounts of energy and materials (*37*). Nanosystem production may prove even more resource-intensive, and some scientists are concerned about the potential hazards associated with inhalation of nanoparticles. Due to such system-level considerations, no technology can be deemed intrinsically sustainable. Renewable or bio-based materials are not necessarily preferable to inorganic materials. Recycled materials are not necessarily preferable to virgin materials. Biodegradable materials are not necessarily preferable to durable materials since industrial ecology networks may recycle spent materials into new applications. It all depends on the system boundaries and requirements.

The system design process itself is undergoing considerable evolution (*38*). Traditional, hierarchical design has proved cumbersome and "brittle" in the sense that a single deviation can disrupt the entire process. Many organizations are experimenting with new techniques such as cooperative, distributed, asynchronous design. Again, this approach is patterned after the self-organizing behavior of living systems. Through advanced communication and groupware technologies, design teams can be distributed geographically and share their ideas and progress via interactive computer displays. For design of complex systems, the ability to iterate rapidly is especially important since design teams need to assess the robustness of alternative designs under a variety of different scenarios and assumptions. In the automotive industry, for example, it is common for the major automakers to co-locate design engineers from their principal "Tier 1" suppliers together with their in-house design teams, enabling a tightly integrated development process.

As mentioned earlier, the design of sustainable systems may benefit from including requirements that address inherent resilience. Characteristics such as diversity and adaptability may not have an obvious relationship to system performance but may contribute to the system's longevity and ultimate success. For example, vehicle designers have increasingly stressed adaptability issues such as reliability and maintainability under extreme conditions, which influence both life cycle performance and cost of ownership. Sometimes the greatest resilience is achieved through design simplicity, which reduces the chances of unexpected failure or disruption.

TABLE 2. Examples of Conventional Sustainability Performance Indicators

economic	environmental	societal
direct	material consumption	quality of life
raw material costs	product & packaging mass	breadth of product or service availability
labor costs	useful product lifetime	knowledge enhancement
capital costs	hazardous materials used	employee satisfaction
operating costs	eco-efficiency	
potentially hidden	energy consumption	peace of mind
recycling revenue	life cycle energy	perceived risk
product disposition cost	power use in operation	community trust
contingent	local impacts	illness & disease reduction
employee injury cost	product recyclability	illnesses avoided
customer warranty cost	runoff to surface water	mortality reduction
relationship	regional impacts	safety improvement
customer retention	smog creation	lost-time injuries
business interruption due to stakeholder interventions	acid rain precursors	reportable releases
	biodiversity reduction	number of incidents
externalities	global impacts	health & wellness
ecosystem productivity loss	global warming emissions	nutritional value provided
resource depletion	ozone depletion	subsistence costs

Evaluating System Performance

A key part of any iterative system development effort is evaluating the anticipated performance of a partially or fully completed design. In many industries this evaluation process is supported by automated tools, known as computer-aided design and manufacture (CAD/CAM), which can perform highly detailed simulations before the system is ever built. Boeing, for example, has honed this approach to the point that its engineers can design a complete aircraft without ever physically building and testing a prototype. However, as the design focus shifts from form and function to the impact on related systems, the evaluation task becomes immensely more challenging. Theoretical computer simulations can be performed to model interventions in biological organisms, ecosystems, or socio-economic systems, but we can seldom ensure their validity.

One alternative approach is *life-cycle assessment*, a systematic method for identifying and quantifying the environmental burdens associated with the life cycle of a product or process (*39*). The approach has also been extended to support life cycle cost accounting (*40*). A life cycle *inventory* can be used to profile the system-wide energy and material consumption and waste generation in terms of flows per functional unit. Life cycle *impact assessment* attempts to evaluate the actual significance of these flows in terms of human effects and ecosystem perturbations, although uncertainties abound. Despite data quality issues, life cycle methods can be useful for relative comparisons of alternative system design options, thus supporting business decisions.

Other evaluation methods include integrative modeling approaches such as *systems dynamics* that attempt to characterize system behavior and anticipate potential evolutionary paths (*41*). For example, recent applications of generalized economic equilibrium models have been helpful in projecting the impacts of different energy technologies upon global climate change (*42*). However, such models cannot be predictive in the classical sense and are often controversial. Recognizing the scientific challenges of integrated system evaluation, the National Science Foundation has initiated a program in *biocomplexity*, which addresses "the dynamic web of often surprising interrelationships that arise when components of the global ecosystem—biological, physical, chemical, and the human dimension—interact" (*43*). The needed linkages among the natural, social, and mathematical science disciplines are still at an embryonic stage.

The usual objective of system evaluation is to quantify selected *performance indicators* that portray the consequences of design choices. Although integrated modeling is not always feasible, the identification of such indicators can be extremely helpful. Even in the absence of quantitative models, it may be possible to develop subjective or qualitative assessments of the directional impacts on key indicators. Table 2 provides example of sustainability indicators that have commonly been used to characterize the performance outcomes of system design or system intervention (*44*). The Global Reporting Initiative has developed a more exhaustive catalog of performance indicators as part of its guideline for sustainability reporting (*45*).

As discussed earlier, it is important to assess not only performance outcomes but also the intrinsic characteristics that contribute to system resilience. Recent studies of energy flows in ecological and industrial systems suggest that new, more elegant, sustainability indicators may be developed based on thermodynamic analysis. For example, it has been conjectured that systems with lower entropy (i.e., higher degree of order) will have a larger life cycle impact on their surroundings (*46*). Calculation of *exergy* (useful energy) appears to offer a promising method for comparative assessment of the ecological efficiency associated with industrial processes (*47*).

Planning System Deployment

The final step in system design is the development of a plan for the release, introduction, and deployment of the system. In the past, product development teams often released their specifications to the manufacturing organization without considering downstream issues associated with component procurement, product distribution, customer support, maintenance, waste disposition, and potential upgrades of the original design. The introduction of "simultaneous engineering" methods and more rigorous stage-gate reviews has helped to shift these considerations back into the design process, thus avoiding delays and unnecessary costs. However, the question of broader system impacts is still poorly understood, and it is rare for design teams to consider them explicitly.

Companies wishing to pursue sustainable system design have a strong motivation to consider the broad implications of an innovative system upon all of the enterprise stakeholders. Each stakeholder group will be touched by the system in different ways and will have their own particular expectations. For example, employees expect the system to be safe and easy to operate. Shareholders expect the system to streamline existing operations and provide an improved return on an investment. Customers expect efficacy and convenience. Public interest organizations expect environmental and social benefits. To understand and manage all of these expectations, it is critical for the company to engage with its stakeholders, understand their concerns, and develop mutual trust so that the system can be introduced successfully. Indeed, the design team should begin considering the deployment phase as early as possible.

The importance of stakeholder engagement is evident in the life sciences field, where companies are developing a host of biotechnology-based products that they claim will enable a shift to sustainable agriculture. One class of these new agricultural products is genetically engineered pest-resistant crops. Proponents claim that this technology will reduce pesticide use, increase agricultural productivity, and lower consumer costs, while opponents are concerned about unforeseen health and environmental impacts (*48*). An open dialogue among interested parties is necessary to establish agreement on the value of these products and the appropriate technical, legal, and ethical conditions for their use. History has shown that it is wise for designers to consider not only the product technology but also the socio-economic system into which it will be introduced.

The need to consider the broader systems context is especially great in developing nations, where agriculture is often central to the indigenous culture. An example is wet rice cultivation in Bali, Indonesia, whose hills are covered with graceful, terraced rice paddies. The rural Balinese lifestyle represents a harmonious equilibrium between society and nature that has persisted for centuries. Rice has long been the island’s most important crop and is deeply embedded in the Balinese social structure. Village life centers around a rice growing association called a *subak*, which organizes community work on irrigation and cultivation systems. Festivals and religious rituals are intertwined with the rice planting, growing, and harvesting seasons. Thus, no matter how promising a new technology may be, any effort to modify the practice of rice growing must begin with a thorough understanding of the ecological and social boundary conditions (*49*).

Conclusion

This paper has provided but a glimpse of the challenges encountered as system design moves from the bounded, controllable scope of traditional products and services to the boundaryless, unpredictable realm of industrial, ecological, and social systems. The increasing connectedness of these systems creates new opportunities but also exposes society to greater risks. Economic threats such as the collapse of markets, political threats such as military aggression, biological threats such as mutant viruses, or ecological threats such as global warming have become the concern of all nations. Moreover, system complexity keeps increasing—serious proposals are being raised for development of sustainable systems on a much larger scale, such as entire cities or regions (*50*). The classic reductionist tools that served so well in a simpler age are no longer adequate. Complex, nonlinear systems cannot be modeled by linking together a fragmented collection of linear models. What is needed is a new language and new metaphors to describe the relationships and dynamic behaviors that characterize these exquisitely complex systems—a new, multi-disciplinary toolkit that begins with connectivity and integration as fundamental themes rather than afterthoughts.

Einstein reputedly said, “Individuality is an illusion created by skin”. Indeed, separateness is a convenient assumption that enables the analysis of objects, people, or companies as if they were independent of their surroundings. However, in practice, this assumption is invalid. System design should proceed with a constant awareness of related systems, boundary conditions, external effects, and potential feedback loops. As design teams continually expand the system boundary, they will need to address new technical challenges in creative ways, for example:

(i) Requirements will include system behaviors rather than just outcomes;

(ii) Predictive modeling will give way to exploratory scenario building;

(iii) Design strategies will rely upon intervention rather than control;

(iv) Robustness will be achieved through resilience rather than resistance;

(v) Risk management will draw upon new concepts such as adaptivity and diversity;

(vi) System state indicators will be based on fundamental energy attributes.

The resilience perspective has important implications for companies that wish to become more sustainable. It is not sufficient for a company to redesign only those systems that it fully controls. At best, this will result in incremental changes that do no harm but do not create substantial benefits either for the enterprise or for society. Instead, companies that wish to ensure their long-term resilience must reach beyond their own boundaries, develop an understanding of the intricate systems in which they participate, and strive for continuous innovation and renewal. In this broader playing field, the rules are different: Strategic adaptation becomes more important than strategic planning, and decision makers need to embrace uncertainty rather than trying to eliminate it. As stated in a recent *Harvard Business Review* article:

> *Any company that can make sense of its environment, generate strategic options, and re-align its resources faster than its rivals will enjoy a decisive advantage. This is the essence of resilience* (*51*).

The history of technological progress has emphasized the conquest of nature, using brute force and standardization to overcome nature’s infinite diversity (*52*). Today, scientists and engineers are learning from nature, discovering patterns that they can apply for the benefit of both humans and the environment. In business as in science, the old Newtonian view of an orderly, machine-like world is giving way to a new view of a chaotic, evolving world. Designing systems that are inherently resilient will support our collective quest for sustainability in this ever-changing, unpredictable universe.

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