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Sustainability and resilience: toward a systems approach

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A comprehensive systems approach is essential for effective decision making with regard to global sustainability, since industrial, social, and ecological systems are closely linked. Despite efforts to reduce unsustainability, global resource consumption continues to grow. There is an urgent need for a better understanding of the dynamic, adaptive behavior of complex systems and their resilience in the face of disruptions, recognizing that steady-state sustainability models are simplistic. However, assessing the broad impacts of policy and technology choices is a formidable challenge, as exemplified in life-cycle analysis of the implications of alternative energy and mobility technologies. A number of research groups are using dynamic modeling techniques, including biocomplexity, system dynamics, and thermodynamic analysis, to investigate the impacts on ecological and human systems of major shifts such as climate change and the associated policy and technology responses. These techniques can yield at least a partial understanding of dynamic system behavior, enabling a more integrated approach to systems analysis, beneficial intervention, and improvement of resilience. Recommendations are provided for continued research to achieve progress in the dynamic modeling and sustainable management of complex systems.

KEYWORDS: decision models, ecosystem analysis, biocomplexity, appropriate technology, globalization, population-environment relationship

Introduction

Global policymakers and strategic planners face difficult choices—for example, what future energy sources will power cities, businesses, and transport systems? Is it possible to sustain economic growth and avoid major disruptions or ecological impacts? Our premise is that the effective pursuit of global sustainability requires a systems approach to the development of policies and intervention strategies. Absent a full understanding of system implications, there is a risk of unintended consequences; for instance, adoption of innovative technologies based on renewable resources (such as bio-based fuels) may have hidden adverse side effects upon agricultural productivity.

Sustainable energy and mobility are closely coupled and are essential services in the supply chain for virtually every economic sector. It has become increasingly unrealistic to perform a self-contained analysis of sustainability in a particular industry without touching upon the broader questions of energy, transportation, climate change, and urban planning. Thus, setting the boundaries for meaningful analysis has become a formidable challenge. Perhaps a more robust approach will be to explore sustainability issues within a global, integrated model, with a magnified resolution for the particular system or sector being studied.

The following discussion explores several fundamental questions:

- What is the current state of scientific knowledge about how complex industrial systems can achieve both short-term continuity and long-term ecological integrity?
- What scientific advances are needed to better understand the linked behavior of complex social, economic, and biophysical systems?
- How can this knowledge be applied to the design and management of future technologies and infrastructures required to meet human needs, particularly energy and mobility?

Drawing upon the experience and insights of intellectual leaders from academia, government, and industry, this essay seeks to provide guidance for future research and collaborative initiatives that offer pragmatic pathways toward sustainability.¹

State of sustainability

Over the last two decades, awareness of sustainability has increased significantly among govern-

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more sustainable business practices. Policymakers worldwide have sought to incorporate sustainability considerations into urban and industrial development. Sustainable development and social responsibility have become increasingly important strategic issues for companies in virtually every industry. Leading manufacturers in the United States and abroad have begun to emphasize sustainability in their internal business processes, external stakeholder and investor relations, and customer value propositions. The following are examples of companies striving to adopt more sustainable business practices.

- Interface, a leading producer of industrial floor coverings, was an early adopter of sustainability principles under the leadership of Chairman and CEO Ray Anderson. By developing products using more sustainable process technologies, Interface has reduced greenhouse gas (GHG) emissions by about 50% and energy consumption by about 33% in five years. Through recovery and reuse of waste materials over a ten-year period, the company has diverted about 84 million pounds of carpet waste from landfills and avoided about US$300 million in waste disposal costs. Redesign of every aspect of Interface’s products has led to a significant decrease in their life cycle-environmental impacts (Bertolucci, 2006).

- Chevron is incorporating sustainability into its business models by developing profitable approaches for meeting public energy needs without bias toward any particular technology. For example, Chevron Energy Solutions (CES) is a fast-growing provider of energy-efficient facility upgrades that are funded by energy savings and can be “bundled” with alternative power (e.g., solar, fuel cells). CES public-sector projects for Federal agencies and various municipalities are reducing resource consumption, avoiding GHG emissions, and saving taxpayer money while benefiting the environment and society. In 2005, CES projects saved 1.2 billion cubic feet of natural gas and 177 million kWh of electricity use and avoided 97,000 metric tons of carbon-dioxide emissions (Davis, 2006).

- General Motors (GM) has adopted a corporate-responsibility framework that combines social responsiveness with corporate values and business goals. Despite its recent financial difficulties, GM recognizes that social and environmental responsibility is critical to its long-term survival. In addition to incremental energy and environmental improvement goals, GM has developed a strategy for reducing fuel consumption and emissions by successive adoption of new propulsion technologies. These innovations range from near-term introduction of flex-fuel vehicles that can run on alternative fuels, to hybrid electric vehicles, to two-mode hybrid systems developed in partnership with BMW and Daimler-Chrysler, to longer-term development of hydrogen fuel cell vehicles (Cullum, 2006).

The above examples indicate advances by progressive companies in every industrial sector. Yet, paradoxically, the more efficient companies become in terms of resource use, the more rapidly the economy grows; this “rebound effect” results in a net increase in industrial society’s ecological footprint (Fiksel, 2006). It is becoming apparent that voluntary, incremental environmental improvements by individual companies will be inadequate to significantly offset the growth of the global economy, and that the rapid growth of China, India, and other Asian economies will likely exacerbate this problem. Ecological-footprint analysis suggests that humanity’s ecological demands already exceed what nature can supply; thus, we have arguably moved into what is termed “ecological overshoot,” effectively depleting the available stock of natural capital rather than “living off the interest” (Venetoulis et al. 2004).

The question of urban system resilience is particularly urgent. By 2030 over 60% of the world’s population will live in cities, many in developing countries; the urban populations of Africa, Asia, and Latin America will go from 1.9 to 3.9 billion over that period. Cities have been extraordinarily resilient; from 1100 to 1800 only 42 cities worldwide were abandoned after their destruction (Allenby & Fink, 2005). Recent incidents, including natural disasters and deliberate attacks, have increased worldwide concerns about urban vulnerability. The resulting demands for greater resilience have in many cases failed to draw from the historical record and systems analysis, and have therefore tended to seriously underestimate the difficulty of enhancing the resilience of complex, adaptive systems such as cities. It is important to develop and implement policies for enhanced resilience, since trends suggest greatly increased complexity for future urban systems (Allenby, 2005).

Need for a systems approach

One approach toward sustainability is offered by industrial ecology—a framework for shifting industrial systems from a linear model to a closed-loop model that resembles the cyclical flows of natural ecosystems. In nature, there is no waste, since one creature’s wastes become another’s nutrients. Thus, industrial ecology provides a foundation for rethink-
ing conventional product or process technologies and discovering innovative pathways for recovery and re-use of waste streams in place of virgin resources. However, the practice of industrial ecology has focused mainly on reducing unsustainability rather than strengthening sustainability’s systemic underpinnings (Ehrenfeld, 2005). Current efforts to achieve sustainability are directed largely at reducing environmental “burdens” measured in terms of resource consumption and waste emissions. Little is understood about the broader impacts of these material and energy flows, or about the qualitative differences among sustainability conditions in different social and economic settings. Therefore, it is helpful to consider ecosystems and industrial systems alike as dynamic, open systems that operate far from equilibrium, exhibiting nonlinear and sometimes chaotic behavior.

To better understand sustainable systems, the scientific research community has increasingly pursued the field of biocomplexity, concerned with characterizing the interdependence of human and biophysical systems (Colwell, 1998). Interdisciplinary research teams are studying the links among industrial systems (energy, transportation, manufacturing, food production), societal systems (urbanization, mobility, communication,) and natural systems (soil, atmospheric, aquatic, biotic), including the flows of information, wealth, materials, energy, labor, and waste. The complexity, dynamics, and nonlinear nature of these interdependent systems imply that the notion of “sustainability” as a steady-state equilibrium is not realistic. Forces of change, such as technological, geopolitical, or climatic shifts will inevitably disrupt the cycles of material and energy flows. Therefore, achieving sustainability will arguably require the development of resilient, adaptive industrial and societal systems that mirror the dynamic attributes of ecological systems.

The concept of resilience has emerged as a critical characteristic of complex, dynamic systems in a range of disciplines including economics (Arthur, 1999), ecology (Folke et al. 2002), pedology (Lal, 1994), psychology (Bonacci, 2004), sociology (Adger, 2000), risk management (Starr et al. 2003), and network theory (Calloway et al. 2000). Resilience can be defined as the capacity of a system to tolerate disturbances while retaining its structure and function (Fiksel, 2003). More specifically, in the business context, we define enterprise resilience as the capacity for an enterprise to survive, adapt, and grow in the face of turbulent change. Enterprises need to grow, just as natural organisms do, and the concept of a static, no-growth enterprise is absurd in the business world. The real challenge, as companies like DuPont and General Motors have discovered, is to increase shareholder value without increasing ma-
Integrated approaches to systems modeling and management

As the need for a systems approach becomes more apparent, the deficiencies of existing “reductionist” models are also revealed. Integrated assessment of sustainable systems cannot be accomplished by simply linking together a collection of domain-specific models. To assess the higher-order interactions among interdependent systems requires new tools to capture the emergent behaviors and dynamic relationships that characterize complex, adaptive systems. Development of such tools has been initiated by a number of multidisciplinary groups worldwide. The following examples illustrate the range of current approaches for modeling and management of complex economic, ecological, and social systems:

- **Biocomplexity in large lake systems**: A multidisciplinary research team at The Ohio State University (OSU) is investigating the complex interactions among biological, physical, and human components of large lake ecosystems (OSU, 2004). Figure 1 illustrates some of these interactions. While a large lake provides amenities, or ecological services, that support economic growth, such growth can degrade these amenities. This team of biologists, ecologists, physicists, economists, geographers, and others is attempting to model the patterns of socio-economic activity, and the potential impacts of policies to protect natural amenities, in the Lake Erie region. Beginning with simple equilibrium models, the project is investigating increasingly sophisticated techniques, including agent-based simulation.

- **System dynamics modeling**: System dynamics was first developed in the 1960s and has evolved into a widespread approach for modeling dynamic, non-linear systems. The Millennium Institute has applied system dynamics to develop the Threshold 21 (T21) model, which combines proven economic-sector models into an integrated framework (Sterman, 2000). The approach uses differential equations to represent changes in stocks and flows, and considers nonlinearity, feedback, and delays. Customized T21 models have been created at a national scale for the United States and Italy, for less-developed countries (Bangladesh, Malawi), and at a regional level in Africa and Indonesia. A typical high-level model structure is illustrated in Figure 2.

- **Ecological engineering and restoration**: Recent catastrophic events, such as the Indian Ocean tsunami and Hurricane Katrina, have highlighted the vulnerability of coastal areas. Scholars have argued that ecologically restored landscapes could have mitigated these disasters and would be more cost-effective and sustainable than traditional engineering solutions such as dams and levees (Mitsch & Jørgensen, 2004). For example, ecological engineering at a watershed-scale in the Mississippi River Basin would not only improve resilience to flooding and enhance ecological processes, but also would significantly reduce the nitrogen load that causes a hypoxic zone in the Gulf of Mexico. Similarly, the restoration of the Mesopotamian marshes in Iraq, destroyed by the Saddam Hussein regime, requires a systems approach to enable sustainable socio-economic recovery (Richardson et al. 2005).

- **Climate impacts on urban infrastructure**: Urban infrastructure systems are long-lived investments with significant impacts on sustainability, and...
are very sensitive to climate and resource demands. Therefore, policymakers need to understand the potential impacts of climate change on infrastructure. Under a grant from the EPA, a group of researchers has used a scenario-based dynamic modeling framework to assess impacts of climate, socioeconomic, and technological changes on the future evolution of urban-infrastructure systems in metropolitan Boston (Ruth & Lin, 2005). Detailed models and indicators were developed for four major systems: transportation, water resources, energy use, and public health.

- **Thermodynamic Life Cycle Analysis (LCA):** A recent approach developed at OSU complements traditional LCA by modeling an industrial system as a network of energy flows governed by the laws of thermodynamics (Ukidwe & Bakshi, 2004, 2005). Traditional LCA methods are mainly “output-side” in that they focus on emissions and their impacts. In contrast, Thermodynamic LCA is an “input-side” approach, relying mainly on data about consumption of natural resources expressed in terms of available energy (exergy). Thus it is particularly useful in the early stages of technology innovation. It accounts for the contribution of ecosystem goods and services to industrial activity, thus quantifying the preservation of natural capital. As shown in Figure 3, the method has been applied to 488 sectors of the U.S. economy, demonstrating a reduction in natural-capital intensity from extraction to manufacturing to service industries.

- **Protection of ecosystem services:** The Millennium Ecosystem Assessment is an ongoing, worldwide effort to evaluate the consequences of ecosystem change for human well-being and to explore plausible ecological futures (Millennium Ecosystem Assessment, 2006). Ecosystem services provide food and other resources, regulate environmental processes, and fulfill human cultural needs. However, decreasing biodiversity, resource depletion, and other changes due to anthropogenic forces are degrading many of these ecosystem services. Strategies for improving ecological resilience include broadening knowledge sources, such as local ecological knowledge; increasing human ability to cope with change and uncertainty; introducing adaptive management practices that integrate monitoring, adaptation, and mitigation; and building practical, social, and scientific networks (Carpenter et al. 2006).

The above examples typify the worldwide groundswell of cross-disciplinary work in sustainability science and engineering. One international group, called the Resilience Alliance, has proposed a new model to characterize the evolution of complex, non-linear systems in terms of an “adaptive cycle” of growth, crisis, transformation, and renewal; thus, mature forests are periodically destroyed by fire or vermin, and then regenerate (Gunderson & Holling, 2002). Similarly, industrial systems are vulnerable to disruptions such as accidents or economic crises, but after a period of “creative destruction,” they enter a new, more resilient growth phase (Hart & Milstein, 1999). Analogous models are being developed in the study of resilience in psychological, social, and cultural systems (Hurst, 1995). While they may provide fresh insights, it is unlikely that any of this new generation of biocomplexity models will achieve a rigorous and scientifically defensible predictive capability. Certainty has become an anachronism, and decision making must occur in the context of a wide spectrum of changing possibilities.

### Applications to energy and mobility systems

Energy and mobility—power and movement—are essential for human society. However, the global economy faces unprecedented challenges in meeting growing energy and mobility demands, due to the clash between economic development and resource limitations. Continued economic expansion raises questions about how existing systems can meet today’s needs without compromising the well-being of future generations. In short, how can energy and mobility services be sustainable?

The energy and transportation industries are exploring a broad portfolio of alternative technologies; yet we have only a vague understanding of the future...
social, economic, and environmental conditions (e.g., demographic patterns) that will influence energy and mobility supply and demand. These conditions will vary enormously across developing and developed nations, urban and rural settings, and different geographies. Nor do we understand the full ramifications of technology choices upon economic vitality, ecological integrity, or community well-being. Therefore, technology development must be accompanied by integrated assessment of the feasibility, eco-efficiency, sustainability, and resilience of these new technologies, providing a sound scientific basis for public policy formulation and research priority setting.

The following are examples of leading-edge efforts to incorporate sustainable systems thinking into the design and development of new energy and mobility solutions:

- **Well-to-wheels life cycle modeling:** In response to concerns about oil dependence and greenhouse gases (GHG), new fuels such as hydrogen and biofuels are being promoted for use in advanced hybrid electric and fuel cell vehicles. Argonne has developed the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model for “well-to-wheels” analysis of life cycle energy and emission benefits (Wang, 2001). The model distinguishes two major stages—well-to-pump and pump-to-wheels—and analyzes the life cycle resource use and emissions associated with production, delivery, use, and disposition of both fuels and vehicles. Careful analysis of future technologies suggests that hybrid electric engines with hydrogen fuel cells will provide the best combination of GHG reduction and urban NOx emissions.

- **Complexity science and sustainable mobility:** The University of Michigan’s SMART (Sustainable Mobility and Accessibility Research and Transformation) Project unites two dozen complexity-science scholars and practitioners in the search for systemic, robust high-leverage solutions to the myriad challenges posed by currently unsustainable transportation and urban development patterns (Gladwin, 2006). Interdisciplinary teams are building agent-based and system-dynamics models of the evolution of the hydrogen infrastructure, transition to use of advanced biofuels, future market penetration of hybrid vehicles, interaction of “new urbanism” and “new mobility,” and evolution of human movement and access systems in the world’s megacities.

- **Systems impacts of alternative fuels:** Selection among alternative fuels requires an understanding of their full implications—for example, using bio-based fuels may imply the use of agricultural pesticides. This is a challenging task due to the complexity of the supply chains, the many alternative raw materials and production pathways, uncertainties in data and models, interactions with economic factors, and the effect of social preferences. An interdisciplinary team at OSU is applying a unique statistical framework for assessing the true impacts of emerging technologies (Bakshi, 2006). It considers the full life cycle impacts at multiple scales, from an individual facility to an industrial supply chain to the global economy. This framework will be used to study alternate fuels including gasoline, ethanol, biodiesel, and hydrogen, and to understand the transitional effects of fuel switching.

While some progress is being made, the scope and complexity of sustainable energy and mobility issues remains daunting. In an integrated global economy, it is no longer possible to deconstruct the interrelationships among global energy flows, resource consumption, and regional economic activity patterns. A case in point is the worldwide response to concerns over global warming. The combined impacts of electric power generation and internal combustion engines account for a majority of today’s global GHG emissions. Significant reductions are being pursued through establishment of carbon trading mechanisms and carbon emission inventory protocols. However, the most rigorous protocol yet developed does not seek to account for non-GHG effects (e.g., ecological impacts) of carbon management projects, although it does include procedures for life cycle analysis of secondary GHG effects (WRI & WBCSD, 2005).

The introduction of market-based systems—for example, cap-and-trade—may yield efficient reductions with currently available technologies, but efforts to develop alternative low-carbon technologies are severely underfunded. The financial discounting calculus of private investment is inadequate to address long-term energy-technology priorities. Instead, coordinated public investment in high-risk, exploratory research is needed, including both technological innovations for sustainable energy and mobility solutions and analytic capabilities to test their resilience at a system level. Moreover, adaptation to climate change requires serious consideration, since global warming impacts are non-linear and may manifest abruptly, with developing nations in the tropics bearing a disproportionate share of the impact. Strategic adaptation will require global cooperation, infrastructure investment, and large-scale engineering to assure the resilience of human society to ecosystem disruptions.
A path forward

The current lack of success in improving industrial sustainability, coupled with the challenges of biocplexity and resilience, indicates that sustainability is a systems problem requiring collaborative solutions. Only a coordinated global effort, with participation from public, private, and nongovernmental organizations, can achieve genuine systemic change. The difficulties encountered with the Kyoto Protocol suggest that such coordination will not be easy. Indeed, global warming issues are perhaps the most tractable, since emissions dissipate in the atmosphere and do not concentrate geographically. There are a number of other pressing ecological issues—soil resilience, biodiversity, water quality, deforestation—that involve interaction of complex local and regional ecosystems. The types of models used formerly to analyze environmental impacts are too limited in scope to address these complex systems. The previous sections have identified a number of emerging approaches to these challenges.

An important research priority for the study of sustainable systems is development of modeling and decision-making approaches that support dynamic, adaptive management rather than static optimization. This requires methods for understanding the full implications of alternative choices and their relative attractiveness in terms of enhancing system resilience. Due to the complexity of coupled systems, researchers should explore the simultaneous use of multiple models that reflect different system interpretations or stakeholder perspectives. Other potentially helpful approaches include simplified analysis of complex, multi-domain models through decomposition, aggregation, or dimensionality reduction; and utilization of biophysical simulations in place of theoretical models—for example, mesocosm experiments for complex ecological systems.

A number of technical advances will likely improve the usefulness of models, including rigorous methodologies for dealing with missing and uncertain information; improved methods for interpretation of multivariate data sets and for multi-objective decision making involving trade-offs among conflicting goals; and novel modeling methods as alternatives to traditional mathematical models, e.g., agent-based models with appropriate utility functions. More generally, there is a great need for operational definitions and metrics for sustainability and resilience in economic, ecological, and societal systems.

While improving modeling techniques and establishing a rigorous science of sustainability is important, a caveat is in order. Excessive modeling efforts may become an excuse for delaying effective political action, leading to “paralysis by analysis” (Cohen & Howard, 2006). Progress in theory-based research needs to be balanced with exploratory policy implementation that will enrich our understanding of sustainability issues in real-world systems. Additional discussions at OSU symposium resulted in the following recommendations for encouraging broad adoption of a systems approach to sustainability:

- Foster transdisciplinary collaboration in university research by creating incentives for interdepartmental teaming on issues of social relevance.
- Improve communications to educators, government, the media, and the general public to convey the urgency of sustainability challenges.
- Develop policy-formulation tools that recognize the complex, interconnected nature of ecological and socio-economic systems, including visualization methods and appropriate metrics.
- Develop mechanisms for integrated dialogue among industry, government, and academia, shifting from an adversarial to a cooperative approach.

Sustainable development in a changing global environment will require resilience at many levels, including human communities and economic enterprises. In the face of ever-increasing global complexity and volatility, it is essential to move beyond a simplistic “steady state” model of sustainability. Instead, we need to develop adaptive policies and strategies that enable societal and industrial institutions to cope with unexpected challenges, balancing their need to flourish and grow with long-term concerns about human and ecological well-being. In particular, addressing the challenge of global warming will require unprecedented international cooperation in both the development of alternative technologies and adaptation to climate change impacts.

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