The industrial revolution brought with it an explosion of machinery and mechanisms to utilize the power and resources of Earth’s natural systems. By the dawn of the twentieth century, U.S. manufacturers led the world in production of finished goods. Much of this success can be attributed to an entrepreneurial spirit, availability of labor through robust population growth and abundant natural resources. Japanese manufacturers in the 1970s and 1980s challenged and overtook U.S. industry in several sectors by practicing quality principles and utilizing lean manufacturing concepts. Companies that survived the market adjustment precipitated by the success of Japan demonstrated an industrial Darwinism—they adapted to survive in the new global economy.

**SURVIVAL SKILLS FOR A GLOBAL ECONOMY**

This phenomenon of learning new survival skills had played out before, with successful companies harnessing steam power in the 1700s, moving materials and goods by train in the 1800s and employing assembly lines in the early 1900s. Today, around the world, there are growing concerns about the sustainability of the industrialized world and its associated excessive wastes and energy consumption. The principle of sustainability asks for behavior that will ensure that future generations have the same opportunities available to them that we presently enjoy.

U.S. competitors around the globe have begun to use sustainability principles as a driver for innovation. When Kubota, a heavy equipment manufacturer in Japan, replaced one of its casting lines, it implemented more environmentally friendly processes for drying of core coatings and cooling of hot castings. The new line resulted in a cycle time of 17.7 hours compared to the previous 132 hours, costs were cut by one-third, and carbon dioxide emissions were lowered significantly. In Europe, Electrolux used life-cycle analysis to produce a more energy-efficient refrigerator that more expensive than a regular refrigerator. The new model was so popular that Electrolux increased its market share.

Manufacturers that fail to learn survival skills ultimately will fall prey to global competitors that are operating under an evolving rule-set. Global companies are directly impacted as Europe and Japan implement policies to achieve closed-loop material flows, promote product stewardship and eliminate hazardous substances. Companies must evaluate and adjust their approaches toward the enterprise, processes, product design and product end-of-use (EOU) with an eye toward realizing a green and sustainable future.

**SUSTAINABILITY: CORPORATE RESPONSIBILITY**

Sustainability is an emerging issue for manufacturing enterprises that recognizes the interdependence of the economy, society and the environment (the three pillars of sustainability). This need prompted the International Organization for Standardization (ISO) to develop a standard for environmental management systems (ISO 14000) and guidelines for social responsibility (ISO 26000).

At Michigan Tech, we have begun to receive many inquiries from companies about how to select supply chain partners that practice sustainability principles or are socially responsible. A variety of criteria, indicators and measures related to sustainability have been proposed and categorized via numerous frameworks. As more manufacturers commit to sustainability principles, the demand for tools and methodologies that consider the total impact of doing business will increase. Given the desire to establish a green supply chain, as a first step, potential suppliers must be evaluated in terms of their economic, social and environmental impacts.

**GREEN IS LEAN**

Early efforts at addressing manufacturing-related environmental problems emphasized pollution containment/prevention approaches. Green/sustainable manufacturing calls for approaches that reduce or avoid waste entirely; for example alternatives to toxic materials, less energy-intensive processes, and process plans to reduce waste. It is evident that such approaches are wholly consistent with the concept of lean manufacturing, and it may be argued that green = lean.
A good example of green practices relates to the copious use of cutting fluids in traditional machining operations, such as boring, drilling and milling (Fig. 1). Industrial hygiene concerns associated with cutting fluid exposure include dermatitis and mist inhalation, while cutting fluids have been found to represent 15% to 20% of production costs. In response to these concerns, dry machining and minimum quantity lubrication technologies are increasingly being employed to reduce fluid use, avoid potentially hazardous emissions and minimize costs.

Technological approaches, however, are not the silver bullet solution to all manufacturing sustainability challenges. Rather, companies must consider the total impact of a product during the engineering design process. U.S. companies lag overseas competitors in considering these “life-cycle” impacts, more and more often are making effective use of life-cycle analysis software to minimize product environmental effects across the life of a product—from material acquisition to manufacturing, use and recycling/disposal.

GLOBAL TRENDS: LESS WASTE, LONGER PRODUCT LIFE
Products should be designed to respond to the needs of consumers. For centuries, tailors, blacksmiths and others in skilled trades made their livelihoods by creating customized products; with the advent of mass production, the emphasis on consumer-tuned products diminished. Today, manufacturers are struggling with the notion of mass customization; that is, integrating the concepts of mass production and individually customized products. One design strategy that seems to offer promise in terms of both mass customization and sustainability is product modularity. With a modular product, elements can be replaced to customize a product for an individual consumer. Modular products offer significant benefits in terms of repairability and upgrading, and undertaking these actions serves to keep a product in service longer.

Of course, the societal pillar of sustainability cannot be neglected. Products must be acceptable to a broad spectrum of users. If consumers are not satisfied with a product, it will fall out of use, and be disposed of prematurely. Another trend is “appropriate” product designs; that is, products for the developing world that are consistent with the needs of individuals in those societies. Thus, as the trend towards globalization becomes more pervasive, societal and cultural differences around the world will drive product designs.

POLICIES PUSH PRODUCT RECOVERY
In the past, manufacturers focused on concepts such as design for manufacturing, design for assembly and robust design. Recently, concepts such as design for the environment, design for disassembly and design for recycling have received much attention. These newer concepts are in large measure being driven by increasing concern for end-of-life (EOL) products. In Europe and Japan, new policies call for the proper handling of EOL products, and are causing manufacturers to rethink traditional product life cycles. It is increasingly the case that used products are taken back by the manufacturer to be refurbished, remanufactured, or recycled—thus avoiding product disposal.

Many business entities in the United States operate profitably by recycling EOL products—automobile recycling is a good example of this. However, the government regulations in Europe and Japan, and the strong role that the original equipment manufacturers play there in product stewardship, are driving product innovation that may erode the competitive position of the United States. A robust product recovery sector in the United States will require an improved reverse logistics infrastructure, enhanced communications among the various value recovery business entities, and technological innovations to support the sector.

GROWTH OF SERVICE SECTOR IN U.S.
It has been suggested that a barrier to sustainability is our reliance on materials to create all the tangible products that pervade our society (iPods, PDAs, TVs, PCs). One strategy for achieving dematerialization is to convert a material-based product to a service-based product, and this conversion has been termed “servicizing” (Fig. 2). Business entities that sell services rather than products tend to be well-positioned for product upgrading, refurbishment, and recycling—all actions that support the goal of sustainability.

The service sector is growing within industrialized countries around the globe— and servicing business opportunities are emerging. One challenge associated with servicizing is the change in mind-set that is required since people will no longer “own” the products they are using. A sense of ownership is clearly an important issue associated with a material-based product, and this emphasizes the importance of the societal pillar of sustainability.
Summary
Manufacturing enterprises face many exciting challenges in formulating internal policies and practices that successfully internalize sustainability concepts. Companies must work with researchers and policy-makers to identify a path forward that nurtures our economy, society, and environment. Businesses that fail to implement novel technologies and methods that address the manufacturing enterprise, processes, product design, end-of-use, and servicizing will be surpassed by others in the global marketplace that are pursuing a sustainable future.

Acknowledgment
Special thanks to Luis Garicloso, Karl Haapala, Margot Hutchins, Kari Jordan, Vishesh Kumar and Julio Rivera for their help in preparing this article.

John W. Sutherland received his BS, MS, and PhD degrees from the University of Illinois at Urbana-Champaign, and is currently the Richard and Elizabeth Henes Chair Professor in the Department of Mechanical Engineering–Engineering Mechanics at Michigan Technological University in Houghton. Professor Sutherland serves as a director for MTU’s Sustainable Futures Institute and has published extensively on topics emphasizing environmentally responsible design and manufacturing. Contact Professor Sutherland at jwsuther@mtu.edu.