Research Journal of Environmental and Earth Sciences 5(4): 193-200, 2013
DOI:10.19026/rjees.5.5714
ISSN: 2041-0484; e-ISSN: 2041-0492

Submitted: November 09, 2012 Accepted: January 11, 2013 Published: April 20, 2013

Research Article

Considering Environmental Sustainability as a Tool for Manufacturing Decision Making and Future Development

[1]Yousef Nazzal, [1]Bassam A. Abuamarah, [2]H.A. Kishawy and [2]Marc A. Rosen
[1]Department of Geology and Geophysics, King Saud University, Riyadh, Saudi Arabia
[2]Faculty of Engineering and Applied Science, University of Ontario Institute of Technology, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada

Abstract: The natural environment and the manufacturing function are becoming inextricably linked. Profitability, productivity and environmental consciousness are increasingly viewed as integral of manufacturing organizations. For manufacturers, environmental sustainability is dependent upon decisions made throughout a product life cycle which includes research, development and manufacturing processes. The present research study describes how environmental sustainability, manufacturing, decision making and green manufacturing are important for the future development and the main priorities in developing new manufacturing processes. The study discussed various models and concepts to make the links among the above mentioned variables and reached to important conclusion that collaboration in needed for increased research and knowledge, exchange in the field of environmental sustainability.

Keywords: Decision making, environment, manufacturing, sustainability

INTRODUCTION

Manufacturers are becoming increasingly concerned about the issue of sustainability. Sustainability was brought to prominence by the Brundtland Commission, which defined it as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987).

Sustainability as been applied to many fields: Regarding energy, for example, Rosen and Rukah (2010) point out that various definitions of energy sustainability have been proposed (Haberl, 2006; Rosen, 2002; Goldemberg *et al*., 1988; Niele, 2005; Wall and Gong, 2001; Zvolinschi *et al*., 2007; Hennicke and Fischedick, 2006; Dunn, 2002; Lior, 2008; Hart, 2006; Beaver, 2000; Bernard and Tichkiewitch, 2008; Curran, 2000; Denkena *et al*., 2007; Lalor, 2008; Lu *et al*., 2007; Schenck, 2000; Yano and Kamiya, 2000; Ciambrone, 1997). The concept of energy sustainability can be viewed as the application of the general definitions of sustainability to energy, but it is in actuality more complex and involved. Energy sustainability involves the provision of energy services in a sustainable manner, which in turn necessitates that energy services be provided for all people in ways that, now and in the future, are sufficient to provide basic necessities, affordable, not detrimental to the environment and acceptable to communities and people.

Sustainability is a critically important goal for human activity and development. At the heart of the concept of sustainable development is the view that social, economic and environmental objectives should be complementary and interdependent in the development process. Sustainable development requires policy changes in many sectors and coherence between them and entails balancing the economic, social and environmental objectives of society, integrating them wherever possible through mutually supportive policies and practices and making appropriate trade-offs where necessary.

Life Cycle Assessment (LCA) is a tool for improving the environmental performance of processes and systems and is often used in sustainability work. In LCA, the environmental impacts of a product or service are analyzed through all phases of its life, with the objective of ensuring the conservation of resources, improving efficiency and reducing environmental damage. According to the ISO series 14040 standards (ISO, 2006), an LCA methodology consists of four phases: goal and scope definition, life-cycle inventory analysis, impact assessment and interpretation, (Hutchins *et al*., 2010). LCA is also used in pollution prevention and green design efforts. Selection of product design, materials, processes, reuse or recycle strategies and final disposal options requires careful examination of energy and resource consumption as well as environmental discharges associated with each prevention or design alternative (Hendrickson *et al*.,

Corresponding Author: Yousef Nazzal, Department of Geology and Geophysics, King Saud University, Riyadh, Saudi Arabia

1998; Harms *et al.*, 2008a, b).

The natural environment and the manufacturing function are increasingly becoming inextricably linked. Progress, profitability, productivity and environmental consciousness are increasingly viewed as integral goals of manufacturing organizations (Sarkis, 2001).

One of the main issues to address in embedding sustainability in manufacturing is that managers, in day-to-day decisions, are rarely provided with the methodology and information needed to take into account the organization's strategic sustainability objectives in a meaningful, consistent and robust manner. Addressing this issue is not easy, as the variables to be taken into account in decision-making are numerous. Also, the data required to make assessments is not always available and can be difficult to obtain, e.g., how much water a process uses or how much carbon dioxide it emits. Furthermore, sustainability issues, e.g., labor practices in supply chain and environmental management, tend to be dealt with in specialist departments rather than by line management. Progress is needed to enable operating managers take into account sustainability issues more effectively in regular decision making, or their ability to achieve sustainability objectives will be seriously inhibited.

This study describes how sustainability, environmental issues, life cycle factors and green manufacturing are important priorities in developing new manufacturing processes. The objective is to improve understanding and to foster advances and collaboration since increased research and knowledge exchange is needed in the application of sustainability to manufacturing, especially in the areas of life cycle assessment and green manufacturing.

SUSTAINABILITY

Sustainability is a concept that means different things to different people. At its most basic it is simply the ability to endure or survive. However, in the context of human development and environmental stewardship, the term has ideological, political, ecological and economic contexts (Pezzoli, 1997) and in this framework it is most commonly seen as a derivation of the term sustainable development (Visser, 2007). Sustainable development is a pattern of resource use that aims to meet human needs while preserving the environment so that these needs can be met not only now, but also for future generations (Smith and Rees, 1998).

The idea that sustainability involves the capacity to endure has significant ramifications. In ecology, sustainability describes how biological systems remain diverse and productive over time. For humans it is the potential for long-term well being, which in turn depends on the well being of the natural world and the responsible use of natural resources. Hawken (2007)

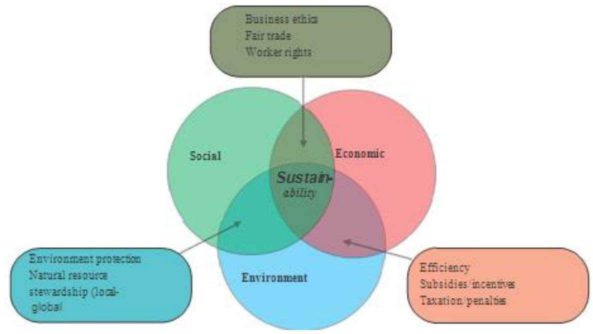

Fig. 1: Three key elements of sustainable development and concepts embodied by their intersections

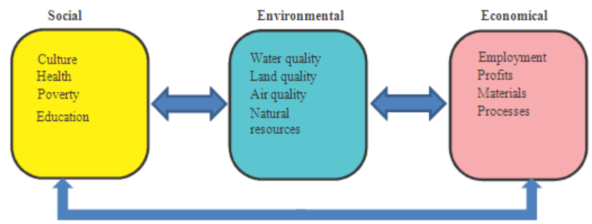

Fig. 2: Interactions among social, environmental and economic aspects of sustainability and some of the factors that comprise them

states, "Sustainability is about stabilizing the currently disruptive relationship between earth's two most complex systems-human culture and the living world.''

Sustainable development can conceptually be broken down into three constituent parts: environmental sustainability, economic sustainability and sociopolitical sustainability (Fig. 1).

Sustainability indicators: An indicator helps identify the status, or direction, or progress relative to a goal. A good indicator highlights problems before they become serious and identifies measures to address the problems. Indicators for a sustainable community identify areas where the links between the economy, environment and society are weak, highlighting where the problem areas lie and approaches to address the problems.

Indicators of sustainability are different from traditional indicators of economic, social and environmental progress. Traditional indicators like economic profitability, health and water quality measure changes in one part of a community as if it is independent of the other parts. Sustainability indicators reflect the interconnectivity of the three different segments and the many factors that comprise them (Fig. 2). This figure indicates that the natural resource base provides the materials for production on which jobs and stockholder profits depend. Jobs in turn affect the poverty rate, which is related to crime. Air and quality and materials used for production affect health and stockholder profits, e.g., cleaning poor quality water prior to use in a process that requires clean water

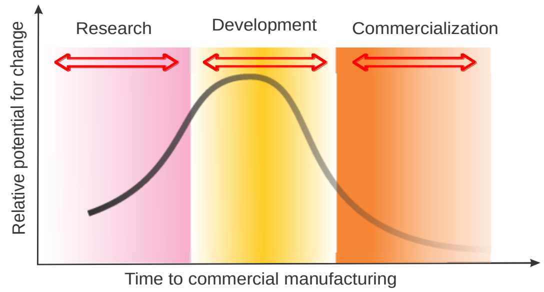

Fig. 3: Environmental health and safety technology engagement model. Modified after Harland *et al*. (2008)

is an extra expense that reduces profits. Similarly, health problems affect worker productivity and health insurance costs, regardless of cause (exposure to poor air quality, toxic materials, etc.).

Sustainability requires an integrated perspective and multi-dimensional indicators that link a community's economy, environment and society. The Gross Domestic Product (GDP), a traditional indicator that measures the amount of money being spent in a country, is not a holistic indicator as it reflects only the amount of economic activity, regardless of how that activity affects the social and environmental health of the community. Nonetheless, GDP is generally regarded as a measure of a country's economic well-being, which assumes the more money spent, the higher the GDP and the better the economic well-being.

Effective indicators have several key characteristics in common:

- **Relevance:** Effective indicators are relevant, in that they reveal necessary information about a system or process.
- **Understandable:** Effective indicators are easily understood, even by non-experts.
- **Reliability:** Effective indicators are reliable, providing information that is trustworthy.
- **Assessable:** Effective indicators are based on accessible data and thus readily assessed.

Sustainable manufacturing processes: Several models for sustainable manufacturing have been developed.

Engagement model: This model is explained through Fig. 3, which illustrates the significant period of time involved in designing a new manufacturing technology and how far ahead of the manufacturing engineers and designers must work to integrate sustainable practices into a new technology. Environmental considerations are not limited to only one point in the development cycle. A more effective approach requires an almost decade-long commitment to integrate sustainability across the entire technology design process, from early research to process development (Harland *et al*., 2008).

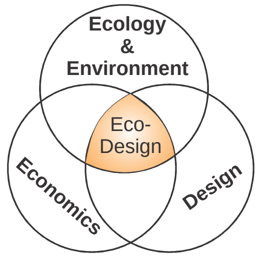

Fig. 4: Eco-design concept, highlighting the key components comprising it

Pre-competitive engagement: The first significant opportunity to influence the design process is in the pre-competitive research phase. This approach not only examines specific requirements but also evaluates sustainability concerns that may not yet be regulated, e.g., energy and utility use and climate change impacts. Early evaluation helps ensure appropriate attention to sustainability, e.g., research can be focused on developing solutions for manufacturing environmental issues.

Research and development: Further research is focused on equipment manufacturers to drive improved environmental efficiency using Design for Environment (DfE) principles, equipment optimization and other methods. Collaboration with vendors helps promote continuous environmental improvements. For instance, Intel worked with suppliers of semiconductor manufacturing equipment and materials to help improve the environmental performance of 300 mm wafer size technologies by about 35% over 200 mm wafer size technologies (Harland *et al*., 2008). Intel operates under a two-year model for new product development which alternates silicon manufacturing technology with microprocessor architecture. The first year of this "Tick-Tock model" introduces a new manufacturing process technology. Each "tick" reduces the size of the semiconductor enabling the manufacture of more semiconductors on a single wafer or the placement of more transistors into an equivalent space. Consequently, each "tick" presents the opportunity to set environmental goals to reduce environmental impact. The second year ("tock") introduces a new chip architecture or design on the same manufacturing technology (Harland *et al*., 2008).

Design for sustainability: Literature on design for sustainability is relatively limited but growing. McDonough and Braungart (2002) describe a triple Bottom Line (3BL), whereby firms balance traditional economic goals with social and environmental concerns. Karlesson and Luttropp (2006) introduce the concept of Eco Design (Fig. 4). Braungart *et al*. (2007) examine eco-efficient strategies focusing on maintaining or increasing the value of economic output while decreasing the impact on ecological systems. Borea and Wang (2007) investigate the relationship between Quality Function Deployment (QFD), life cycle analysis and contingent valuation and compare these with customer willingness to pay for environmentally benign products. Grote *et al*. (2007) propose a product development approach using DFX (Design for X) tools, life cycle analysis and TRIZ (theory of inventive problem solving), to help the design engineer employ eco-design principles without trade-offs on economic issues, while Sakao (2007) proposes the integration of Quality Function Deployment (QFD), lifecycle analysis and TRIZ into a methodology for environmentally conscious design.

Nonetheless, several gaps exist in the literature on design for sustainability. One missing element is an engineering design tool permits a design team to evaluate complex tradeoffs between environment, customers, process parameters and other constraints (Johnson and Srivastava, 2008). Honda and Toyota suggest an engineering approach within lean product development systems as the best approach to managing product development activities, as this approach allows a firm to examine design alternatives throughout the product development process and thereby to evaluate more fully costs and benefits of design for sustainability issues (Morgan and Liker, 2006). A feature of set-based or lean product development is a focus on key customer needs and manufacturing capabilities, which tends to eliminate errors before they occur and results in built-in quality. Inclusion of environmental and sustainability issues in constraints and design parameters results in a broader range of design alternatives and allows a firm to evaluate the effect of sustainability issues and on product cost, project complexity and process design in a more holistic and data driven manner than afforded by just using modified versions of engineering design tools such as QFD, DSM (Design Structure Matrix), DFMA (Design for Manufacturing and Assembly) and DFSS (Design for Six Sigma) (Johnson and Srivastava, 2008).

MANUFACTURING

Manufacturing sustainability: Sustainability has come to be interpreted in many ways, encompassing as much as required to satisfy a particular objective. For this reason, the definition requires further clarification to be applicable in manufacturing. Since its introduction, organizations have tried to apply this concept to industry. One idea, the “triple bottom line,” emerged as the business case for sustainability. This philosophy suggests a more holistic approach that relies on the principles of economic prosperity, environmental stewardship and corporate responsibility (Elkington, 1998). Other similar approaches exist using associated terms: people planet profits, sustainable management, ecological sustainability, etc.

Metrics are needed to measure the achievement of sustainability. The idea of monetizing sustainability catalyzed the evolution of the triple bottom line into the sustainability ecosystem (Stokes, 2009). The tenets of environmental compliance, communication and operational efficiency provide a measurable outcomes supported by traditional business directives. Results can be measured or “monetized” based on outcome priorities and delivery of business performance (Rockwell Automation, 2009).

Increased productivity reduced operating costs and work effort and enforced regulatory compliance have typically been drivers that justify investments in plant optimization. Any business directive, on its own, can be related to more efficient use of necessary resources (energy, raw materials, human, information, equipment). Taken together as an optimization strategy, a solution’s capability to meet the immediate plant needs impacts positively business in the future, for the company as well as future generations. For energy systems, present manufacturing has evolved to improve operating cost structures, including load curtailment and shedding, energy monitoring and control of generators, HVAC systems and thermal and chiller plants. These traditional uses for manufacturing were developed without a focus on sustainability, but can help meet the goals of sustainability, as explored in the following sections (Rockwell Automation, 2009).

Manufacturing strategy and the environment: General manufacturing strategy considers both product and process. The perspective is more general than the traditional volume/variety matrix and production process comparisons (Hayes and Wheelwright, 1979). A “practices” section is included to incorporate organizational and philosophical elements of manufacturing strategy. Within these categories a “technological” dimension is integrated with manufacturing strategy, since manufacturing is a technologically driven function. Some issues related to technology, manufacturing and the environment have been presented. A common equation for determining the environmental impact EI of society is:

$$EI = P*A*T$$

where,

P : Population
A : Affluence
T : Technology (Johnson and Srivastava, 2008)

Since population and affluence are relatively controversial and difficult to constrain, technology appears to be the measure that can be improved (Graedle and Allenby, 1995; Hart, 1997).

Issues in the technological category affecting the natural environment and manufacturing include process, product and practice. These categories exhibit significant overlap, as well as a synergistic and dependent relationship. Technology can be defined as the knowledge of an organization (MacAvoy, 1990).

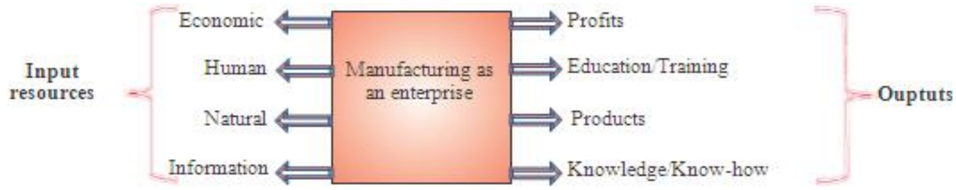

Fig. 5: Basic flows of manufacturing treated as a broader enterprise

Technological developments are not necessarily associated with single organizations and most innovations, especially strategic environmental ones, have resulted from inter-organizational (even intergovernmental) efforts. For example, industry consortia such as the European Eureka program, the National Center for Manufacturing Sciences in the US and Ecofactory in Japan, each have a significant research focus on environmentally conscious manufacturing practices and technology. Further, technology transfer and diffusion throughout industry is weak (Sarkis, 2001).

Process: Manufacturing process developments from an environmental perspective can be linked to reduction, reuse, recycling and remanufacturing. Closed-loop or zero-emission manufacturing objectives involve reuse of wastes or by-products within the manufacturing system, which is viewed as an industrial ecosystem. The success of a closed-loop manufacturing system requires both prevention (e.g., substitution) and reuse capabilities. The flexibility of manufacturing technology within an organization also requires capabilities for material flexibility (Sarkis, 2001). Equipment within the manufacturing environment that can accommodate variations in material flows readily helps organizations maintain competitiveness while utilizing sustainable practices.

Product: Product strategy within a manufacturing function is most closely associated with Design for the Environment (DFE) and Life Cycle Analysis (LCA). Product and materials flexibility are necessary for product development and materials substitution, for environmental and competitive reasons, as product life cycles are expected to continue to decrease as product customization increases. Making products environmentally benign by design also can contribute to the successful introduction and maintenance of products. One categorization that organizations can effectively use, which has been recommended by the US Environmental Protection Agency, is based on the Malcolm Baldrige criteria and includes the following elements:

- Environmental leadership
- Strategic environmental quality planning
- Environmental quality management systems
- Human resources development
- Stakeholder emphasis
- Environmental measurements
- Environmental quality assurance

Practices: Practices can strategically impact on the manufacturing function and include evolving benchmarking and performance measurement schemes. These schemes aid production managers in developing and maintaining new environmental programs and technology. Another environmentally-based influence of concern to organizational manufacturing practices is ISO 14000 certification. ISO 14000 certification, which should be used in support of additional organizational practices, since on its own it does not guarantee environmental successful (Sarkis, 2001).

Manufacturing decision making: Manufacturing decision makers normally address the economic aspect of sustainability; in the past it was the only dimension of sustainability addressed. Recently, corporations have paid more attention to environmental sustainability. Tools and concepts such as carbon footprint estimation, life cycle assessment, design for the environment and product stewardship are becoming increasingly common. Engineers in industry now consider such measures as resource consumption and emissions of toxic substances, greenhouse gases, atmospheric pollutants and liquid wastes. Such performance measures are critical to improvement, as the efficacy of change to the industrial system on environmental sustainability cannot be judged without such metrics (Hutchins *et al*., 2010).

There are four fundamental flows into and out of a manufacturing enterprise (Fig. 5). In some ways, business aims to reconfigure physical, human, information and financial resources so that the financial resources exiting the system are larger than those that enter. Sustainability requires that corporations maintain the integrity of social and environmental system while undertaking this reconfiguration. Efforts have been expended to integrate measures of sustainability into the decision-making practices associated with adjusting these flows. An important challenge remains identifying appropriate sustainability indicators.

For a business to act consistently with sustainability principles, it must understand how it impacts sustainability through sustainability indicators. Parris and Kates (2005) review 12 efforts to define the indicators of sustainability ranging in scale from global to local and identify up to 255 indicators of sustainability which vary greatly in terms of the level of control that business decision makers have over them, the effort required to incorporate them into decision making and the financial burden associated with their implementation.

CONCLUSION

Environmentally sound business practices require good models and theories that have roots in reality, are developed in close collaboration with industrial and environmental decision maker and account for the extended producer responsibility principle. Environmental Life Cycle Assessment (ELCA) in combination with the evaluation of toxicity and risk potential is expected to become increasingly important to foster sustainability and help manufacturers. This methodology allows the quick calculation of toxicity potential with limited input information. The obtained data are part of eco-efficiency analysis and are useful to manufacturing decision makers for toxicity assessment.

The present study indicates the importance of conceptual integration of key concepts related to sustainability, like environmental life cycle assessment, in manufacturing decision making (Fig. 6). The present examination of these concepts leads to several important conclusions:

- Governments and agencies needs to better incorporate environment factors into policies, programs and operations.
- Governments and agencies need to continue working both internally and externally with partners to advance greener procurement to forward overall environmental mandates.
- A more wide-range and integrated approach, encompassing economic, social and environmental considerations, is needed for sustainability. For instance, more efficient and recyclable packaging designs are needed to make packaging more sustainable.
- Better tools and methods for manufacturing are needed that support the triple bottom line of sustainability.
- By implementing an integrated approach that goes beyond the factory and incorporates environmental life cycle assessment, the manufacturing industry can move towards environmental sustainability.
- Significant research and collaboration is needed between industry and academics in the field of sustainability, manufacturing and environmental life cycle assessment. Also needed to support environmental sustainability across the entire product life cycle is standardization of data collection and robust data sets.
- Manufacturing sustainability should include the following measures:
  - Enhanced sustainability governance, indicate how an organization measures sustainability and required monitoring.
  - Improved environmental tactics to control a company's environmental footprint.
  - Modified working conditions and workforce culture to support sustainability.
  - Addressing customer and supplier needs, e.g., desired product safety procedures.
  - Social community engagement, allowing companies to work with local communities and to ensure ethical, responsible conduct.

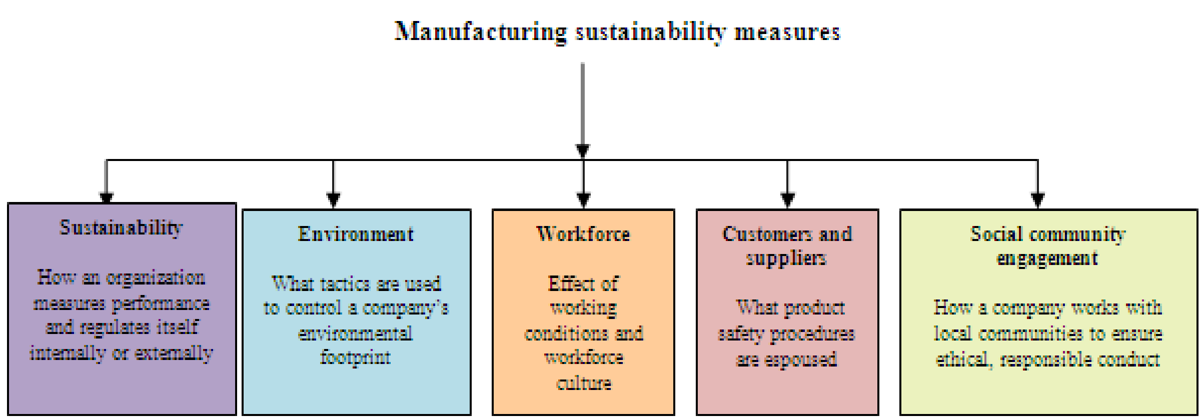

Fig. 6: Sustainability measures for manufacturing

ACKNOWLEDGMENT

The project was supported by the Research Centre, College of Science, King Saud University.

REFERENCES

Beaver, E., 2000. LCA and total cost assessment. Environ. Prog., 19(2): 130-139.

Bernard, A. and S. Tichkiewitch, 2008. Methods and Tools for Effective Knowledge Life-Cycle-Management. Springer, Berlin.

Borea, M.D. and B. Wang, 2007. Redesign methodology for developing environmentally conscious products. Int. J. Prod. Res., 45: 4057-4072.

Braungart, M., W. McDonough and A. Bollinger, 2007. Cradle-to-cradle design: Creating healthy emissions: A strategy for eco-effective product and system design. J. Clean. Prod., 15: 1337-1348.

Ciambrone, D.F., 1997. Environmental Life Cycle Analysis. Lewis Publications, Boca Raton, pp: 160.

Curran, M.A., 2000. Life cycle assessment: An international experience. Environ. Prog., 19(2): 65-71.

Denkena, B., M. Shpitalni, P. Kowalski, G. Molcho and Y. Ziporilou, 2007. Knowledge management in process planning. CIRP Annal., 56(1): 175-180.

Dunn, S., 2002. Hydrogen futures: Toward a sustainable energy system. Int. J. Hyd. Energ., 27: 235-264.

Elkington, J., 1998. Cannibals with Forks: The Triple Bottom Line of 21st Century Business. New Society Publishers, Stony Creek, CT, pp: 20-45.

Goldemberg, J., T.B. Johansson, A.K.N. Reddy and R.H. Williams, 1988. Energy for a Sustainable World. Wiley, New York.

Graedle, T.E. and B.R. Allenby, 1995. Industrial Ecology. Prentice-Hall, Englewood Cliffs, NJ, pp: 5-60.

Grote, C.A., J.M. Jones, G.N. Blount, J. Goodyer and M. Shayler, 2007. An approach to the EUP directive and the application of the economic eco-design for complex products. Int. J. Prod. Res., 45: 4099-4117.

Haberl, H., 2006. The global socioeconomic energetic metabolism as a sustainability problem. Energy, 31: 87-99.

Harland, J., T. Reichelt and M. Yao, 2008. Environmental sustainability in the semiconductor industry. Proceeding of the IEEE Symposium on Electronics and the Environment, May 19-22, San Francisco, pp: 1-6.

Harms, R., T. Fleschutz and G. Seliger, 2008a. Life cycle management of production facilities using semantic web technologies. CIRP Annal. Manufact. Technol., 59: 45-48.

Harms, R., T. Fleschutz and G. Seliger, 2008b. Knowledge based approach to assembly system reuse. Proceedings of the 9th Biennial ASME Conference on Engineering Systems Design and Analysis, pp: 295-302.

Hart, S.L., 1997. Beyond greening: Strategies for a sustainable world. Harvard Bus. Rev., 75(1): 66-76.

Hart, M., 2006. What is an Indicator of Sustainability? Sustainable Measures. West Hartford, CT 06137-0502, Retrieved from: www.sutainablemeasures.com.

Hawken, P., 2007. Blessed Unrest: How the Largest Movement in the World Came into Being and Why No One Saw it Coming. Viking, New York, pp: 172.

Hayes, R.H. and S.C. Wheelwright, 1979. The dynamics of product-process life cycles. Harvard Bus. Rev., 57(2): 127-136.

Hendrickson, C., A. Horvath, J. Satish and L. Lave, 1998. Green design: Economic input-output models for environmental life-cycle assessment. Environ. Sci. Tech. Policy Anal., 32(7): 184A-191A.

Hennicke, P. and M. Fischedick, 2006. Towards sustainable energy systems: The related role of hydrogen. Energ. Policy, 34: 1260-1270.

Hutchins, M.J., J.S. Gierke and J.W. Sutherland, 2010. Development of a framework and indicators for societal sustainability in support of manufacturing enterprise decisions. Trans. NAMRI/SME, 38: 759-766.

ISO, 2006. 14040: 2006 Environmental Management-Life Cycle Assessment - Principle and Framework. 2nd Edn., ICS 13.020.10; 13.020.60, pp: 20, Retrieved from: www.iso.org/iso/catalogue_detail?csnumber = 37456.

Johnson, D.D. and R. Srivastava, 2008. Design for sustainability: Product development tools and life cycle economics. Proceeding of the 39th Annual Meeting of the Decision Sciences Institute, Baltimore, Maryland, November 22-25: 1711-1716.

Karlesson, R. and C. Luttropp, 2006. Eco-design: What's happening - An overview of the subject area of eco-design and the study in this special issue. J. Clean. Prod., 14: 1291-1298.

Lalor, P., 2008. Simulation Lifecycle Management: Maximizing the Business Advantages. Industry Week, Sept. 8.

Lior, N., 2008. Energy resources and use: The present situation and possible paths to the future. Energy, 33: 842-857.

Lu, S.C.Y., W. Elmaraghy, G. Schuh and R. Wilhem, 2007. A scientific foundation of collaborative engineering. CIRP Annal., 56(2): 605-634.

Macavoy, T.C., 1990. Technology Strategies Case Notes. Darden School of Management, University of Virginia, UVA-ON-0656, Charlottesville, VA.

McDonough, W. and W. Braungart, 2002. Design for the triple top line: New tools for sustainable commerce. Corp. Environ. Strat., 9(3): 1711-1716.

Morgan, J.M. and J.K. Liker, 2006. The Toyota Product Development System: Integrating People, Process and Technology. Productivity Press, New York.

Niele, F., 2005. Energy: Engine of Evolution. Elsevier, Oxford, UK.

Parris, T.M. and R.W. Kates, 2005. Characterizing and measuring sustainable development. Ann. Rev. Environ. Res., 28: 559-586.

Pezzoli, K., 1997. Sustainable development: A transdisciplinary overview of the literature. J. Environ. Plann. Manag., 40: 549-574.

Rockwell Automation, 2009. Manufacturing Execution System for Sustainability. Publication SUST-WP001A-EN-P, New York, USA, pp: 1-10.

Rosen, M.A., 2002. Energy efficiency and sustainable development. Int. J. Glob. Energ. Issue., 17(1-2): 23-34.

Rosen, M.A. and Y. Abu Rukah, 2010. Energy sustainability: A key to addressing environmental, economic and social challenges. Proceeding of the 5th International Green Energy Conference, June 1-3, Waterloo, ON, Canada.

Sakao, T., 2007. AQED-centered design methodology for environmentally conscious product design. Int. J. Prod. Res., 45(18-19): 4143-4162.

Sarkis, J., 2001. Manufacturing's role in corporate environmental sustainability: Concerns for the new millennium. Int. J. Oper. Prod. Manag., 21(5-6): 666-686.

Schenck, R., 2000. Using LCA for procurement decisions: A case study performed for the US Environmental protection agency. Environ. Prog., 19(2): 110-116.

Smith, C. and G. Rees, 1998. Economic Development. 2nd Edn., Macmillan, Basingstoke, UK.

Stokes, S., 2009. Get Ready for Green 2.0. AMR Research. Düsseldorf, Germany.

Visser, W., 2007. Sustainability. In: Visser, W., D. Matten, M. Pohl, N. Tolhurst (Eds.), the A to Z of Corporate Social Responsibility. Wiley, West Sussex, UK.

Wall, G. and M. Gong, 2001. On exergy and sustainable development. Exergy Int. J., 1: 128-233.

WCED (World Commission on Environment and Development), 1987. Our Common Future. Oxford University Press, Oxford, New York.

Yano, M. and K. Kamiya, 2000. The national LCA project in Japan. Environ. Prog., 19(2): 140-145.

Zvolinschi, A., S. Kjelstrup, O. Bolland and H.J. Van der Kooi, 2007. Exergy sustainability indicators as a tool in industrial ecology. J. Ind. Ecol., 11: 85-98.