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Innovation in sustainable manufacturing education

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Abstract
Sustainable value creation entails generating value for all stakeholders from economic, environmental and social perspectives. In a manufacturing context, creating sustainable value requires product, process and systems level innovations to enable near-perpetual closed-loop material flow across multiple life-cycles; it also requires understanding the complex interactions of the socio-technical systems with the natural environment for emergent synthesis so sustainable value creation can occur harmoniously and continuously. However, current educational curricula with traditional disciplines is fragmented and do not represent the multi-disciplinarity or the integration needs; it is now necessary to work at the interface of the various disciplines to address the complex issues that are brought about through sustainability. Thus, to create sustainable value through sustainable manufacturing will require transformational and innovative reforms in education with an overall paradigm shift to provide the future generation of engineers, scientists and managers the necessary technical knowledge, skills and capabilities. This paper presents recent trends in developing such innovative educational programs in sustainable manufacturing. Also, the technological challenges posed by the need for implementing viable innovative sustainable manufacturing educational programs inevitably require fundamental studies on total life-cycle products, closed-loop manufacturing processes and integrated production systems extending beyond to the entire supply chain operations. This paper is aimed at tackling these significant challenges by essentially developing sustainable value propositions for all forms of educational programs (formal degrees and certificate level programs, professional/continuing education programs, short courses and web-based interactive learning programs, etc.) to incorporate the new knowledge needed to promote value-added sustainable manufacturing at product, process and system levels.

Keywords:
Sustainable manufacturing, innovation, education, curriculum development

1 INTRODUCTION

With continuously increasing awareness and the need for sustainable products and processes, a strong emphasis needs to be placed on developing education and training programs including relevant curricula for engineers and scientists of the future to provide the basic theories and applications of sustainability science involving product life-cycle engineering and sustainability principles for societal, economic and environmental benefits. Over the last few decades, traditional manufacturing/production engineering educational programs have long depended on curricula based on concurrent engineering methodologies covering product and process designs, functional design development, concept selection for product design, materials and process selection, process planning including assembly analysis, etc., all aimed at optimally selected designs and manufacturing practices for economic manufacturing. These programs however suffer from the lack of consideration of sustainability principles.

While significant progress is being made in new curriculum development and/or updating current curriculum to incorporate sustainability principles and practices in manufacturing, more needs to be done, particularly in the broader sustainability perspective, to cover the entire production system. This would require full understanding of the total life-cycle effects involving innovative methods for products, processes and systems involved in manufacturing. Attempts must also be made to maintain the holistic objective given by the overall sustainability requirements in industrial production for which educational programs must be significantly revised. It has been shown that efforts to make manufacturing more sustainable must also consider sustainability issues at all relevant levels: product, process, and system [1]. At the product level, there is a need to move beyond the traditional 3R concept promoting green technologies (reduce, reuse, recycle) to a more recent 6R concept forming the basis for sustainable manufacturing (reduce, reuse, recycle, recover, redesign, remanufacture), since this allows for shifting from an open-loop, single life-cycle paradigm to a more meaningful, closed-loop, multiple life-cycle paradigm [2]. At the process level, there is a need to model and achieve optimized technological improvements and develop process planning to reduce energy and resource consumptions, toxic wastes, occupational hazards, etc. without compromising the product quality or the manufacturing productivity [3]. At the system level, there is a need to consider all aspects of the entire supply chain, by taking into account all the major life-cycle stages – pre-manufacturing, manufacturing, use and post-use – over multiple life-cycles [4].

This paper presents an overview of recent trends, and new challenges involved in developing educational programs

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and/or updating curriculum for producing next generation engineers and scientist with adequate and relevant knowledge for achieving overall sustainability at the product, process and system levels in industrial production.

1.1 The role of education and training in sustainability applications for manufacturing

Sustainability as the driver for innovation*:* Numerous studies and in-depth analysis of sustainability concepts and applications have shown that sustainability is a driver for innovation. The most notable among these studies include an early work published in the Harvard Business Review [5] which presents a five-stage approach with central challenges and competencies required, and the innovation opportunities discussed for each stage:

Stage 1: Viewing compliance as opportunity;
Stage 2: Making value chains sustainable;
Stage 3: Designing sustainable products and services;
Stage 4: Developing new business models; and
Stage 5: Creating next practice platforms.

A more recent MIT study [6] shows that many companies are generating profits from sustainability. They recommend five practices to accomplish this:

- Need to change the business model
- Leading from the top to integrate the effects
- Measuring and tracking sustainability goals and performance
- Understanding the customer expectations for sustainability in terms of value and cost
- Collaborating with individuals, customers, businesses and groups beyond the boundaries of the organization

Innovation promotes accelerated growth in manufacturing*:* It is well-known that innovation in industrial production with advancement of product and process technologies leads to technological advances with competitive advantage, and this promotes accelerated growth in manufacturing. Sustainable products and processes are known to be innovative, and they contribute to societal and environmental benefits, too.

Manufacturing is the engine for wealth generation and societal well-being*:* National economy of any country heavily depends on the manufacturing capacity and the diversity of products and processes developed for its population, and for marketing to other nations. Developed and developing nations have shown the pivotal role of manufacturing in job creation, societal well-being and national economic advancement.

Societal well-being and economic growth heavily depend on the level and quality of education and training*:* Education and training of workforce are essential elements for economic and social growth of any nation. Such education and training programs in sustainability are also a strategic requirement for nations, communities and individuals. Thus, innovation is vital for promoting sustainable manufacturing that is an engine for more sustainable growth and education and training play a strategic role in enabling this future.

1.2 Sustainable manufacturing: Definition

Sustainable manufacturing deals with three integral elements: products, processes and systems. To achieve sustainable production, each of these three integral elements is expected to demonstrate:

(a) reduced negative environmental impact,
(b) offer improved energy and resource efficiency,
(c) generate minimum quantity of wastes,
(d) provide operational safety, and
(e) offer improved personal health

while maintaining and/or improving the product and process quality.

There are numerous definitions and descriptions for sustainable manufacturing. However, almost all such definitions fall short of showing the connectivity among the above integral elements. Sustainable manufacturing offers a new way of producing functionally superior products using sustainable technologies and manufacturing methods through the coordination of capabilities across the supply chain. Thus, integrated sustainable manufacturing focusing on product, process and system levels must ultimately enable sustainable value creation for all stakeholders. This entails following a co-creative model to generating value through sustainable manufacturing where value generation is approached broadly from a systems thinking perspective by taking account of the dependencies between the producer, the consumer as well as the product/service and the wider social and natural environment, as opposed to manufacturers simply providing value independent of the other stakeholder needs (providing value model) or value being assessed based only on the interactions between the product/service and the environment (Adaptive Model) (Figure 1) [7].

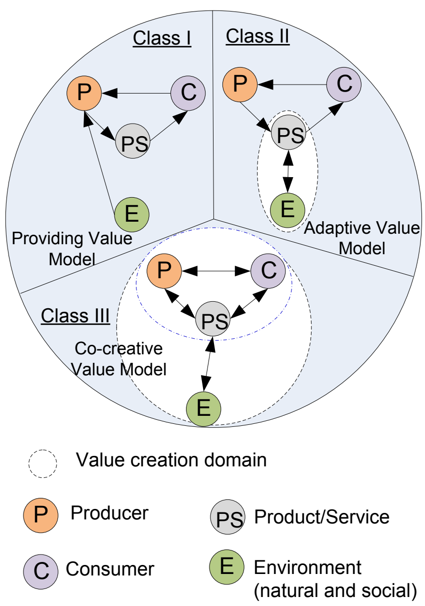

Figure 1: Sustainable value co-creation models (Based on [7]).

2 REVIEW OF RELEVANT LITERATURE ON EDUCATIONAL NEEDS FOR SUSTAINABLE MANUFACTURING

There is a large domain of literature on engineering education applied to manufacturing in general. More recently, an increasing trend is noted in published material covering specific aspects of environmental and sustainable engineering programs. This is due continuing awareness of sustainability issues by the society at large and the new and attractive research funding opportunities that have come to exist. As the industrial sector continues to embrace sustainable manufacturing technologies, universities and institutes of higher learning are increasing their curriculum development activities to match the industry needs and to satisfy the stakeholders at large.

An early work presents an educational program for sustainable futures largely based on environmental concerns [8]. Concepts of global competitive sustainable manufacturing are shown for creating the knowledge base of competitiveness and sustainability from education, research and innovation [9]. To accomplish sustainable industrial systems enabling the delivery of high value, the emerging role of systems thinking in education, research and industrial practices was emphasized with specific recommendations [10]. Educational challenges involved in preparing future engineers in the U.S. with sustainable engineering fundamentals were summarized from the efforts of Center for Sustainable Engineering (CSE) through documented activities of national level workshops, roadmap assessment and the development of an electronic library [11]. This follows an earlier extensive study of sustainable engineering education and research in U.S. universities [12-14] and an international comparative study of sustainability education [15]. Also, a more specific comparative study of undergraduate educational programs in selected U.S. universities has been reported [16]. New challenges involved in developing educational programs to introduce design for sustainability principles and practices were also presented [17]. More recently, an extensive review of sustainable manufacturing research emphasizes the need for developing educational programs for future engineers with a broad-based understanding of product and process design, material processing and manufacturing by highlighting their influence across the entire life-cycle [18].

3 SUSTAINABLE VALUE FROM INNOVATIVE PRODUCTS, PROCESSES AND SYSTEMS

3.1 General Background

Developing innovative products, processes and systems is a significant aspect of sustainable manufacturing, and it involves a holistic approach to manufacturing different from the traditional manufacturing practices where the quality and performance characteristics are measured and quantified independently, often with no consideration of the effects of other integral elements. While integrated product – process design methodologies have largely been based on concurrent engineering applications, involving team of “experts” from multi-disciplinary fields, territorial boundaries and responsibilities with varying reporting structures of team members, unless centrally managed, often have prevented these experts from going across the boundaries of their units and/or organization to participate in developing innovative products, processes and systems. The emerging holistic and integrated approach requires all stakeholders to work together on common objectives with total commitment. To enable innovation in sustainable manufacturing, innovation must be embraced at the product, process and systems levels with close interactions among each other as shown in Figure 2.

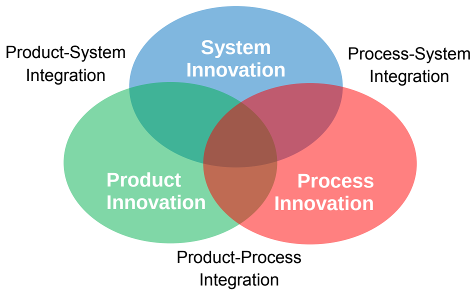

Figure 2: Innovation in sustainable manufacturing at integrated product, process and system levels.

Fully integrated sustainable manufacturing will emerge as an effective platform for developing sustainable products from sustainable processes and with related system integration. Examples of constituting innovative aspects in sustainable manufacturing are shown in Figure 3 for each component of innovation. The innovation must enable developing an integrated sustainable value system for sustainable manufacturing with numerous value-contributing factors: value propositions such as technological value, socio-economic value, socio-political value, and socio-environmental value, etc., can be derived from this integrated system.

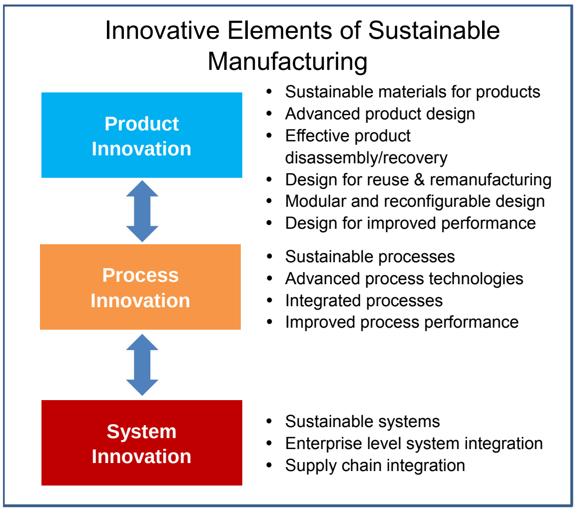

Figure 3: Examples of innovative aspects in sustainable manufacturing at product, process and system levels.

3.2 Sustainability Issues at the Product and Process Levels

Since there are multiple streams of energy, material and waste/emission involved at different stages over a product’s life, the necessity of considering the total life-cycle in order to evaluate a product’s sustainability score for comparison between different designs, or between different production strategies, is well recognized. Graedel [19] presented an extensive study of streamlined life-cycle analysis (SLCA) methods in a pioneering textbook covering various methodologies, including matrix approaches using target plots, and considering five major product life-cycle stages: pre-manufacture; manufacture; product delivery; use; and recycling. Subsequently, the product delivery, including transportation, was considered as only one among several delivery activities involved in all stages of the product's life-cycle, hence the simplified total life-cycle of a product was assumed to consist of four key stages – pre-manufacturing, manufacturing, use and post-use [2]. To achieve multiple product life-cycles with the goal of near-perpetual product/material life, design and manufacturing practices for next-generation products must consider these product life-cycle stages using a more innovative 6R approach, and then build a comprehensive systems model to cover products, processes and systems to enable value creation through innovation at all levels.

Product sustainability*:* Several researchers have considered the environmental performance and the associated economic and societal effects of products, largely intuitively, and offering limited quantitative descriptions. Thus, these analyses mostly remain non-analytical and less scientific in terms of the need for quantitative modeling of product sustainability. Moreover, the partial treatment and acceptance of the apparent effects of several sustainability-contributing measures in relatively simplistic environmental, economic and societal impact categories has virtually masked the influence of other contributing factors such as product's functionality, manufacturability, reusability with multiple life-cycles, etc. Consideration of a total and comprehensive evaluation of product sustainability can lead to reduced consumer costs over the entire life-cycle of the product, while the initial product cost could be slightly higher in some cases. This benefit is compounded when a multiple life-cycle approach is adopted on the basis of continuous material flow. The overall economic benefits and the technological advances involving greater functionality and sustained quality enhancement are far too great to outscore with the current practice. The technological and societal impacts are also significant.

Recent research on product sustainability evaluation shows a consistent trend towards the long-range development of a product sustainability rating system for all manufactured products. This rating would be expected to represent the "level of sustainability" built in a product by taking into account all major contributing sustainability elements and their sub-elements. Early work shows the following six product sustainability elements [2]:

(a) Environmental Impact
(b) Societal Impact (Safety, Health, Ethics, etc.)
(c) Functionality
(d) Resource Utilization and Economy
(e) Manufacturability
(f) Product's Recyclability/Remanufacturability

These interacting elements and sub-elements need to be fully studied for their effects on product sustainability. Other influencing elements and sub-elements will be identified as appropriate. This systematic study should provide a solid foundation for involving relevant "priority roles" and "trade-offs", when this project is extended to the next level. Our preliminary work in this area also considered ratings at all three levels (sub-element, element and overall).

Process sustainability*:* The primary objective of identifying and defining the various contributing elements and sub-elements of manufacturing process sustainability is to establish a unified, standard scientific methodology to evaluate the degree of sustainability of a given manufacturing process. This evaluation can be performed irrespective of product life-cycle issues, recycling, remanufacturability, etc., of the manufactured product. Manufacturing processes are numerous, and depending on the product being manufactured, method of manufacture, and their key characteristics, these processes differ very widely. This makes the identification of the factors/elements involved in process sustainability and the demarcation of their boundaries complex. For example, if the production process of a simple component is considered, it goes through a few clearly defined production stages; component design, tool/work material selection, metal removal/forming, finishing, packaging, transporting, storage, dispatching, etc.

It is extremely difficult to consider all of these stages in evaluating manufacturing process sustainability though they either directly or indirectly can contribute to the manufacturing process sustainability. Also, the processing cost largely depends on the method used to produce the part/component and the work material selected. In a never-ending effort to minimize the manufacturing costs, the industrial organizations are struggling to maintain the product quality, operator's and machine safety, and power consumption. If the processing includes the use of coolants, lubricants, emission of toxic materials or harmful chemicals, this poses environmental, safety and personnel health problems. In general, among the various factors, the following six factors can be regarded as significant to make a manufacturing process sustainable:

(a) Energy consumption
(b) Manufacturing cost
(c) Environmental impact
(d) Operational safety
(e) Personnel health
(f) Waste reduction

The motivation for recent sustainability studies of manufacturing processes comes from recent efforts in developing a manufacturing process sustainability index. The idea in developing this concept is to isolate the manufacturing process from the global picture of sustainability, and to develop it up to the "level of acceptance" for common practice in industry. The observations and the existing modeling capabilities can be used to model the impact of the manufacturing process on contributing major sustainability parameters. Models developed for manufacturing variables can be integrated for achieving optimized performance. Finally, the optimized results can be used in defining the sustainability rating for the specific manufacturing process with appropriate weighing factors.

3.3 Sustainable Products from Sustainable Processes

As efforts continue to develop sustainable products and sustainable manufacturing processes, a recent trend observed is to develop sustainable products from sustainable processes, thus enabling, potentially, doubling environmental, economic and societal values of product manufacture. Case studies involving the use of sustainable machining methods such as dry, cryogenic and minimum quantity lubrication (MQL) machining have been shown for producing functionally superior machined products with significantly improved product sustainability, in terms of performance, quality and life [20]. Figure 5 shows a schematic of activities involved in producing sustainable products from sustainable processes.

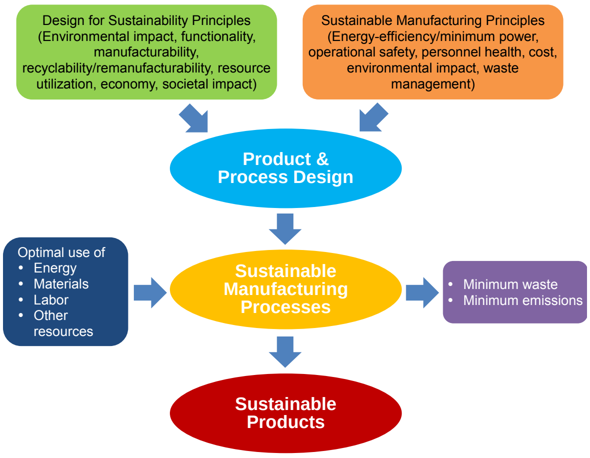

Figure 5: Proposed methodology for producing sustainable products from sustainable processes (Adapted from [20]).

3.4 Sustainability Issues at the Systems Level

The transformation of raw materials into more sustainable products through sustainable manufacturing processes requires careful coordination of various activities across and within the organizations that span the closed-loop supply chain. Historically, these supply chains have been designed and managed as open-loop systems aimed at coordinating the activities of independently managed organizations with the main emphasis being on maximizing profit [1]. From a systems perspective, developments in socio-technical systems theory [21] helped understand that manufacturing systems and support organizations are in effect technical systems embedded within social systems whose interactive complexities must be understood to manage these entities to achieve the desired performance.

However, for sustainability improvement, manufacturing system and supply chain design and operation must not only consider the behavior of the socio-technical system, but also integrate complexities of the interactions between the socio-technical systems and the natural environmental environment to minimize the unintended consequences. Also, systems are adaptive, and emergent entities [22] characterized by various feedback and reinforcing loops without a proper understanding of which can lead to catastrophic behaviors of these systems given the complex contexts in which they operate. Thus, sustainable manufacturing systems and supply chains must be designed and managed as integrated socio-techno-environmental systems from a total life-cycle perspective by considering the interfaces and interactions among the different sub-systems. Also, given the intractable nature of systems for sustainability, the ability to think and communicate systematically, or systems thinking, becomes an important capability that must be developed to increase the capability to design and manage such systems [21].

Given the above context, the design practices for sustainable manufacturing system and supply chain design must consider a variety of interactions between the methods and technical models, all the stakeholders who have an influence on the system or can be influenced by the system as well as the complex dependencies between these aspects and the natural environment. Evaluating the system performance from these aspects therefore will require comprehensive sustainability metrics at the plant, enterprise and supply chain levels; the adaptive and emergent behavior of the system designed with all other interactive systems, must be assessed through predictive models. The design protocol for designing such sustainable systems is shown in Figure 6.

Recent advances in sustainable supply chain design that follows some aspects of the approach shown in Figure 7 have addressed coordinating the design of sustainable products and systems by considering the social, economic and environmental implications of a variety of stakeholders; the time-variant, adaptive behavior of supply chains and implications on sustainability performance is also considered [24], [25]. Developing tools such as sustainable value stream mapping (Sus-VSM) to assess the socio-techno-environmental aspects at the manufacturing systems level have also been presented [26]. The modeling risks due to negative and unintended influences of economic, environmental and social implications from and on other inter-dependent systems (Figure 6) through probabilistic Bayesian Belief Networks can provide methods to develop mitigations/interventions to improve sustainability of manufacturing systems and supply chains [27].

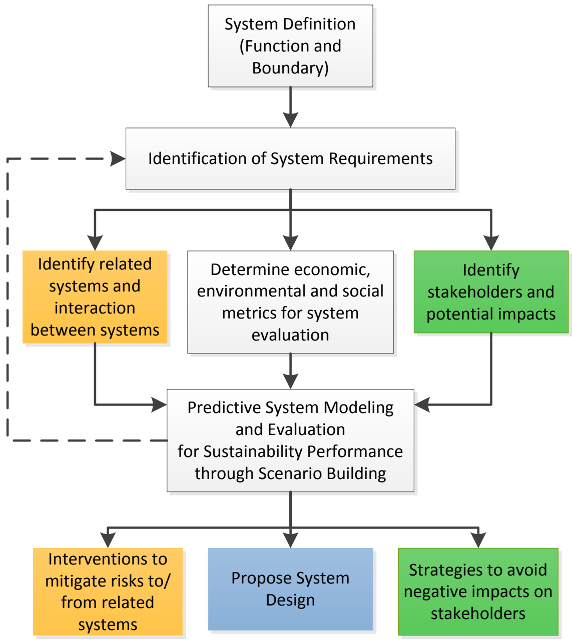

Figure 6: Protocol for Sustainable System Design (adapted from [23])

4 INNOVATIVE EDUCATIONAL PROGRAMS FOR SUSTAINABLE MANUFACTURING

Significant innovative content involved in sustainable manufacturing makes the education and training programs for next generation engineers and scientists challenging, and this should lead to new motivations for embarking on excellence in education and training programs. The International Framework for Action in Education developed following the initial discussions at the Rio Earth Summit in 1992, and further refined during subsequent gatherings, reiterates that, education must no longer be seen as an end, but the means to generate sustainable value. The need to disseminate knowledge skills and know-how to enable sustainable manufacturing as well as more sustainable consumption patterns are identified as one of the core-requirements for reorienting educational needs not only in developing countries, but also in developed regions of the world [29].

The new curriculum in sustainable manufacturing must be based on the strength of partnership among the three major participants: university, industry and state and federal organizations (Figure 8). The societal and environmental benefits, along with the economic gains, are achievable with this strategic partnership, which brings in education and training as the major linkage for these three units as shown in Figure 8. Traditional educational programs are generally evolved around the need for educating engineers and scientists the basic knowledge on physical and natural sciences, engineering materials, product design engineering and manufacturing sciences. These disciplines are taught in isolation and with no significant exposure to real world applications including social and human sciences.

The new curriculum will focus on multi-disciplinary, interconnected and environmentally and societally-relevant subjects knitted together to form the fabric of "sustainable manufacturing". Significant emphasis will be placed on developing new teaching and learning modules covering environment, economy and society, along with a thorough understanding of the natural cyclic systems representing the bio-complexity and reusable material bases including recyclability of materials. Design for sustainability principles will be taught to cover all relevant elements of practical sustainability focusing on the 6Rs (reduce, reuse, recycle, recover, redesign and remanufacture), and near-perpetual material flow from the closed loop approach involving four product life-cycle stages: pre-manufacturing, manufacturing, use and post-use. Also, the significance of marketing, innovation, management, ethics, regulations, policies, etc., will be covered in this proposed approach to provide a much broader knowledge base for next generation engineers and scientists who will learn science-based principles sustainability and will apply them to manufacturing. Also, manufacturing engineering science courses will include material on process performance enhancement, sustained quality, improved health and safety along with knowledge on cleaner manufacturing processes. The progression of cumulative learning at undergraduate and graduate levels extending up to PhD was shown in our prior work [17].

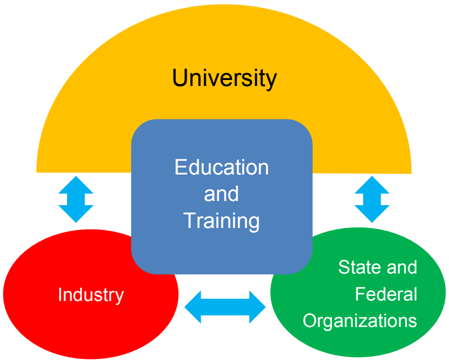

Figure 8: Integral role of university, industry and state and federal organizations in education and training (Adapted from [20]).

The proposed education and training program in sustainable manufacturing is an extended program beyond the traditional degree programs shown above. Identified five basic elements of this curriculum structure are: (a) new formal degree program based on instruction, lab work and projects at undergraduate and graduate levels, (b) a multi-disciplinary certificate program to provide a broader perspective on sustainability for engineers working in industry, (c) industry-relevant short courses, (d) professional/continuing educational programs, and (e) web-based online programs.

4.1 General background on strategic educational needs

Traditional product design and manufacturing methods are based on a range of product characteristics such as functionality, performance, cost, time-to-market, etc. Product design and manufacture in the 21st century will require a greater integration of life-cycle, sustainable product/process designs and their implementation in the manufacture of engineered products. This will apply to both consumer products in high volumes and small varieties and highly customized products in low volumes and large varieties. In particular, the design and manufacturing practices for next-generation products need to undergo major changes to include concerns that span the entirety of the traditional life-cycle, and ultimately from the perspective of multiple life-cycles/multi-uses involving perpetual material flow. Novel design methodologies, innovative manufacturing techniques, and effective tools must be developed to simultaneously address the total life-cycle issues including:

- Reduction of manufacturing costs
- Reduction of product development time
- Reduction of material use
- Reduction of energy consumption
- Reduction of industrial wastes
- Repair, reuse, recovery and recycling of used products/materials
- Environmental and societal concerns

This paradigm shift in product design and manufacture requires optimized methods incorporating environmentally conscious, energy-efficient, lean manufacturing methods with product maintenance, disassembly, material recovery, re-use, re-manufacturing and recycling considerations. It promotes a systems thinking in the design of new products and processes and calls for attention to the interests of all stakeholders. It requires devising new design methodologies, manufacturing processes, post-use processes, and enterprise resource planning in order to simultaneously achieve the multiple objectives of improving a company's profitability, bringing new products to market rapidly, conserving natural resources, while managing environmental concerns.

To enable sustainable products using sustainable processes, new capabilities to model and analyze complex interactions between various sub-systems at manufacturing system and supply chain level are required. Understanding and solving complex problems caused by the interactions between different aspects and stakeholders of the system to create sustainable value will require more intense cooperation between the various scientific disciplines as well as between the pure and social sciences [28]. This requires careful planning and a systematic development of new curriculum for implementation at all levels, beginning from high schools through to undergraduate and graduate programs. The following sections deal with topics that would make significant contributions to the proposed new educational programs.

4.2 Undergraduate education

One of the major concerns with undergraduate education is the increased compartmentalization of disciplines, which in the end produces graduates who are unable to view problems from any perspective other than taught in their own disciplines. All sustainability problems, including those in sustainable manufacturing involve complex issues, particularly at the systems level, that cannot be addressed by looking through the lens of one single discipline. Future engineers, scientists and managers must be taught skills and capabilities to view complex sustainability problems from different perspectives to enable robust solutions that are resilient to different externalities that may be encountered. However, the traditional model for undergraduate education in engineering and manufacturing has been highly discipline-specific, not providing the broad and well-rounded education needed to address sustainable manufacturing problems.

A recent unique effort in this area is an innovative team taught cross-disciplinary course for undergraduate students intended to transform science, technology, engineering and mathematics (STEM) education [29]. The course taught at the University of Kentucky brings together students and faculty from four different colleges—Engineering, Design & Architecture, Education and Business/Economics. In this course, titled 'Systems Thinking for Sustainability, students are trained to address sustainability issues from a systems thinking perspective by using problem-based learning. From a teaching perspective, challenges identified through this experience will be relevant when transformative reforms to undergraduate sustainable manufacturing education are being planned.

4.3 Graduate education

For the most part, graduate education in sustainability studies has so far been limited to a focus on environmental technologies and business/management/leadership activities and programs mostly driven by popularity. Public awareness of the environmental effects of industrial production has largely been centered around programs that deliver courses aimed at assessing and managing the environmental impacts such as pollution studies, toxicity, public health and safety, waste minimization, emission studies, coolant reduction, restriction of the use of chemicals, product and process quality studies, reliability, monitoring and maintenance of machinery and equipment, etc. Sustainable manufacturing education at the graduate level must have a much broader emphasis not just limited to environmental aspects but integrating social aspects and covering product, process and system to advanced capabilities to model, evaluate and analyze these three elements to advance sustainability.

4.4 Professional development and continuing education/training

Industry-based practicing engineers and professionals seek to pursue continuing educational programs in an effort to update their knowledge with recent advances and future developments. Short courses, workshops and professional development programs on dedicated topics organized and delivered by academic institutions, professional societies and other consulting groups help to achieve targets for such professionals, often with full sponsorship by their employers. Also, signature conference series sometimes offer such programs as add-on components. A range of topics covered by such programs focusing on sustainable manufacturing has in recent times been elevated to be among the most popular programs as the employers continue to recognize the economic impact of implementing sustainable manufacturing for their products and processes.

4.5 Other educational needs

As pointed out by many, 'basic education provides the foundation for all future education and learning' [28]. Thus, to derive effective outcomes from the transformational reforms to undergraduate, graduate and professional education for sustainable manufacturing in the long run, the 'seeds' of knowledge and the value system to appreciate the importance of sustainability in general, as well as sustainable production and also the importance of more responsible behavior and sustainable consumption, must be developed at an early age [28]. As such, educational reforms to increase innovative capabilities through sustainable manufacturing must begin even earlier, possibly at the pre-kindergarten level and continue through K through 12 levels; such a broad approach will help transform the mental models of the future workforce to effectively participate in shaping a sustainable future through sustainable value creation.

5 CONCLUSIONS

Innovative sustainable manufacturing can become the engine for sustainable growth by not only promoting economic growth, but also enabling social well-being and environmentally conscious practices. Creating value through sustainable manufacturing will require innovation at the product, process and systems levels across the total life-cycle and through multiple life-cycles. The complex challenges that must be balanced when promoting sustainable manufacturing at these different levels will necessitate the future generation of engineers, scientists and managers who have the required education and training to address these challenges for sustainable value creation. While important strides have been made in reviving the educational curricula to meet some of these needs, there are still significant reforms necessary to develop multi-disciplinary and cross-cutting educational programs that will also transcend the traditional boundaries between disciplines. New models for sustainable manufacturing education must aim to change the mindsets of future generations beginning at an early age then fostered through formal education at undergraduate, graduate and professional levels. Further, with an increasingly web-savvy future generation, there is also a need to extend the dissemination of such educational programs through new mechanisms such as on-line degree programs.

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