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# Design for Sustainability (DFS): New Challenges in Developing and Implementing a Curriculum for Next Generation Design and Manufacturing Engineers*

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*Trends in innovative product design and manufacture require a paradigm shift in traditional methodologies because they are becoming increasingly ineffective for applications built for sustainable futures. The well-known concept of sustainable development, which is based on sustained growth for environmental, economic and societal benefits, is brought into focus for highlighting the significance of product design and manufacture. The technological challenges posed by the need for implementing innovative design and manufacture call for a need for developing and implementing new educational and training programmes for next generation design and manufacturing engineers. We aim at tackling these challenges with a proposed new curriculum at five different levels. Perpetual material flow and multi life-cycle/multi-use self-healing materials, innovative product and process design and development are in the core of the proposed design for sustainability educational programmes.*

**Keywords:** product design; manufacturing; sustainability; education; curriculum

## INTRODUCTION

RECENT TRENDS AND ADVANCES in product design and manufacture have placed a strong emphasis on developing advanced curricula to provide engineers of the future with the basic theories and applications of product manufacturing involving product life-cycle engineering and sustainability principles for societal, economic and environmental benefits. Traditional design for manufacturing educational programmes 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 the best design and manufacturing practices for products and economic manufacturing. Growing environmental concerns associated with product life-cycle issues have in recent times inevitably forced the need for new topics in curriculum development largely to cater for societal needs. This has resulted in many universities and colleges developing new courses in product life-cycle engineering and environmentally conscious product design and manufacture at undergraduate and graduate levels. While significant progress is being made in new curriculum development, a lot more needs to be done particularly in the broader sustainability perspective. This would require full understanding of the total life-cycle effects involving innovative methods for products and processes in manufacturing.

From the global and societal viewpoint, it is necessary to see the specific application of the well-known sustainability definition in product design and manufacture. The World Commission on Environment and Development (also known as the Brundtland Commission) defines Sustainable Development as 'the capacity to meet the needs of the present without compromising the ability of future generations to meet their own needs' [1]. In only 12 years—from 1987 to 1999—the world's population increased by 20 per cent, from five to six billion. Current projections predict the population reaching around 9.1 billion people by 2050, nearly 150 per cent of today's 6.3 billion [2]. Everything else being equal, meeting even the most basic needs of such a global population will require significant material resources and energy. With their continual depletion, the need for effective and economic use of renewable energy sources and reusable materials becomes significant for economic, environmental sustainability to provide for the world's growing needs. Within this context,

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current educational programmes require major revisions to accommodate scientific principles and applications of sustainability engineering to meet future challenges. Engineers and product and process designers of tomorrow will be expected to demonstrate their knowledge and training in product and process sustainability. A paradigm shift is called for such educational challenges. This will cover the development and application of broader sustainability principles in product design for manufacture encompassing the wider applications of Design for Sustainability (DFS) to allow all related Design for X elements [3]. Recent studies presenting the blueprints and roadmaps for engineering education emphasize new curriculum and course development for education and training of the future workforce in innovative design and manufacturing [4–6].

A historical perspective of sustainability engineering educational programme development is well presented in a recent paper [7] covering the early programmes in the 1990s at the Technical University of Denmark, ETH, Zurich, University of Technology, Netherlands, University of Stuttgart, etc. A growing number of national and international educational institutions are currently embarking on new curriculum development for life-cycle and environmental engineering educational programmes, most notably the initiatives at the Queen's University [7], Michigan Technological University [8], Georgia Tech [9], University of Rhode Island [10], Texas Tech [11], University of Missouri—Rolla [12], University of Technology, Australia [13] and Auckland University, New Zealand [14] are making significant progress. More recent efforts include the sustainable development educational programme at the Engineering Department in Cambridge University [15–16], green design educational program at Carnegie Mellon [17] and the project-based sustainable design programme at MIT [18]. A notably increasing number of colleges and universities are currently initiating programmes on sustainability. The American Society for Engineering Education (ASEE) urges the need for integrating sustainability studies in the traditional engineering curriculum [19] along with the declaration made by 11 global educational organizations, including UNESCO, UNU, IAU, ICS, WFEO, for greening the school curriculum [20]. Also, the joint conference on engineering education and training for sustainable development organized by WFEO, UNEP, WBSD and ENPC (France) provides a solid structure for implementing sustainability educational programmes at undergraduate and graduate levels in universities [21].

New educational challenges are associated with the development of design for sustainability principles and their applications in product design and manufacture. Below we outline these new challenges posed in the traditional evaluation of product life-cycle principles, and the sustainability evaluation methods for products and processes. We shall propose a new curriculum for sustainability engineering with five levels for implementation and describe recent experience in developing a sustainability programme at the University of Kentucky.

## NEW CHALLENGES FOR EDUCATION IN PRODUCT DESIGN AND MANUFACTURING

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 this 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 address simultaneously total life-cycle issues including:

(a) Reduction of manufacturing costs;
(b) Reduction of product development time;
(c) Reduction of material use;
(d) Reduction of energy consumption;
(e) Reduction of industrial wastes;
(f) Repair, reuse, recovery and recycling of used products/materials;
(g) Environmental and societal concerns.

This paradigm shift in product design and manufacture obviously requires optimized methodologies incorporating environmentally conscious, energy-efficient, lean manufacturing methods with product maintenance, disassembly, material recovery, reuse, remanufacturing 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 in our living environment. It requires the devising of new design methodologies, manufacturing processes, post-use processes and enterprise resource planning in order to achieve simultaneously the multiple objectives of improving a company's profitability, bringing new products to market rapidly, conserving natural resources, with environmental concerns.

The new challenges posed by this natural transformation of societal need call for a comprehensive overhaul of the current educational programmes to accommodate courses that provide the scientific principles and applications of the entire life-cycle of manufactured products including multi-use and multi-life materials with perpetual material flow, new materials and process technologies for sustainable designs, and manufacturing processes and systems for sustainability. This requires careful planning and a systematic development of new curricula for implementation at all levels, beginning from high schools through to undergraduate and graduate programmes.

*Product life-cycle concepts*

With the rapid growth in industrialization, the environmental concerns of society reflecting the need for 'design for environment', are often associated with the use of materials and energy, and this has so far led to a significant number of social reforms and regulations by local, state and federal authorities, all aimed at improving societal wellbeing, health, safety, economy and environmental protection. Generally targeted activities include: global climate changes, loss of biodiversity, ozone depletion and toxic emissions, availability of water and its quality, resource depletion, sub-optimal land use, acid deposition, smog, oil spills, effects of radiations, odour, thermal pollutions and landfill exhaustion [22]. The role of disassembly in life-cycle assessment was heavily emphasized in a CIRP keynote paper [23]. Design for sustainability elements and their correlation with evolving life-cycle issues were shown by Tipnis in 1993 [24]. Subsequently, environmental concerns were associated with product disassembly [25], and this was followed by material separation and design for bulk recycling analysis [26–28]. A design for environment software was developed in 1999 [29]. A series of ISO standards have been developed to disseminate and implement the basic principles of life-cycle assessment and management, and these standards provide the framework, goals, and scope, impact assessment methods, etc. [30–33].

The traditional product life-cycle methods have long depended on evaluating the life-cycle in confined five stages: (a) Resource extraction (b) Manufacturing operation (c) Packaging and Shipping (d) Customer use (e) Obsolescence. Designing products with improvements in each of these stages would enhance the life-cycle value of products. While each product is expected to satisfy the designed functionality along with provisions for manufacturability, assembly requirements, reliability, safety, serviceability, environmental compliance, etc., the end-of-life options are generally not well thought out. The economic and environmental analyses performed on products impacting the society are almost entirely developed for a single life-cycle of the product. The material recovery aspect along with possible reuse/multi-use opportunities associated with economic gains and societal and environmental benefits are hardly evaluated. Indeed, the perpetual material flow across multiple life-cycles and multi-use benefits are not considered in traditional practices in the current manufacturing units. The last stage of the above traditional life-cycle analysis, which has been performed by other than the manufacturers, has in recent years increasingly come to be the responsibility of the manufacturers with various lease and take-back options.

Colleges and universities are continuing to become interested in conducting research on product life-cycle issues and on designing manufacturing processes for greater sustainability through sponsored project activities from industry and various funding agencies, but the growth of educational programmes to reflect the current research trends has been very slow. Therefore, a leapfrogging reform in educational programmes would be necessary. Moreover, industry expectation of this new knowledge and skills in sustainability from a fresh graduate joining the workforce is high. Thus, the educational challenges are great for producing adequately qualified and trained engineers, even though meeting these challenges is a mammoth task.

*Assessment of product sustainability*

Almost all previous research deals with product's environmental performance and its associated economic and societal effects largely intuitively, and qualitative descriptions offered are little and are often difficult to measure and quantify. Thus, these analyses mostly remain non-analytical and less scientific in terms of the need for quantitative modelling of product sustainability. The complex nature of the systems property of the term 'product sustainability' seems to have limited the development of a science-base for 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 current practice. The technological and societal impacts are also great for undertaking such an innovative approach.

Current research on product sustainability evaluation shows a consistent trend towards the long-range development of a Product Sustainability Index (PSI) for all manufactured products. This index would be expected to represent the 'level of sustainability' built in a product by taking into account all major contributing sustainability elements and their subelements. Our preliminary work shows the following six product sustainability elements—see Fig. 1 [34]:

1) Product's Environmental Impact;
   - Life-cycle factor (including product's useful life span)
   - Environmental effect (including toxicity, emissions, etc.)
   - Ecological balance and efficiency
   - Regional and global impact (e.g. $CO_2$ emission, ozone depletion, etc.)
2) Product's Societal Impact (Safety, Health, Ethics, etc.);
   - Operational safety
   - Health and wellness effect
   - Ethical responsibility
   - Social impact (including quality of life and peace of mind, etc.)
3) Product's Functionality;
   - Service life/durability
   - Modularity
   - Ease of use
   - Maintainability/serviceability
   - Upgradeability
   - Ergonomics
   - Reliability
   - Functional effectiveness
4) Product's Resource Utilization and Economy;
   - Energy efficiency/power consumption
   - Use of renewable source of energy
   - Material utilization
   - Purchase/market value
   - Installation and training cost
   - Operational cost (including labour cost, capital cost, etc.)
5) Product's Manufacturability;
   - Manufacturing methods
   - Assembly
   - Packaging
   - Transportation
   - Storage
6) Product's Recyclability/Remanufacturability;
   - Disassembly
   - Materials separation
   - Recyclability
   - Disposability
   - Remanufacturing/reusability (including multiple use of materials and repeated material flow cycles).

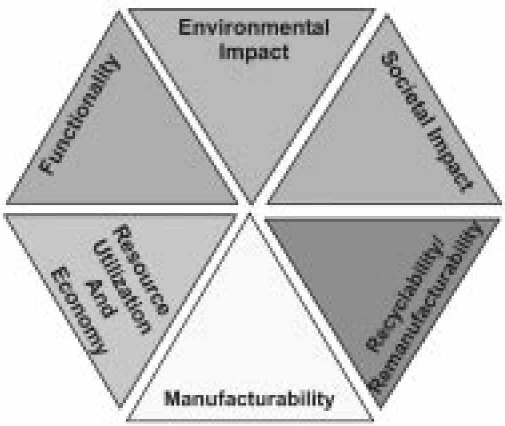


Fig. 1. Factors affecting product sustainability [34].

The above interacting elements and subelements need to be fully studied for their effects on product sustainability.Other influencing elements and subelements 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 indicates that the ratings are needed at all three levels (subelement, element and overall) [34]. While the rating of each factor group contributes to the product's sustainability, the composite rating will represent the overall 'sustainability index' of a product—Product Sustainability Index (PSI). This overall product sustainability can be either in terms of a percentage level, or on a 0–10 scale, or on a letter grade such as 'A', 'B', 'C', etc. Figure 2 shows such an approximate product label to be formulated. Current research thus emphasizes the need for a universal and comprehensive trademark for easy and convenient societal application.

Figure 3 shows the integral role of all sustainability elements and subelements in generic form with equal weighting for each of the six major elements.

*Sustainable manufacturing processes*

The primary focus in identifying and defining the various contributing elements and subelements of manufacturing process sustainability is to establish a unified, standard scientific methodology to evaluate the degree of sustainability of a given manufacturing process [35]. This evaluation can

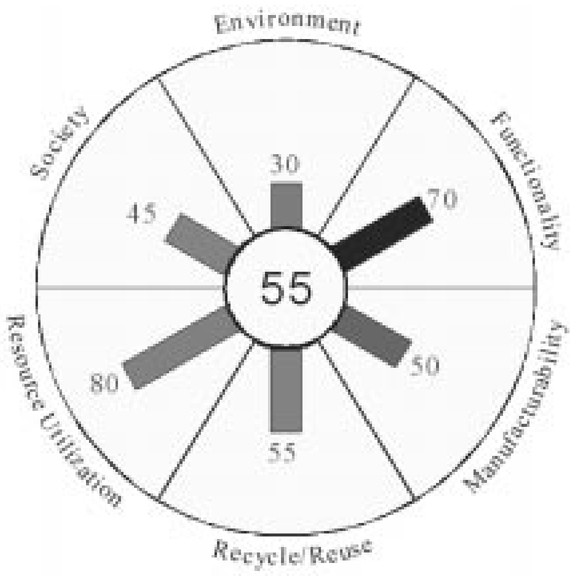


Fig. 2. Proposed sustainability label for manufactured product [34].

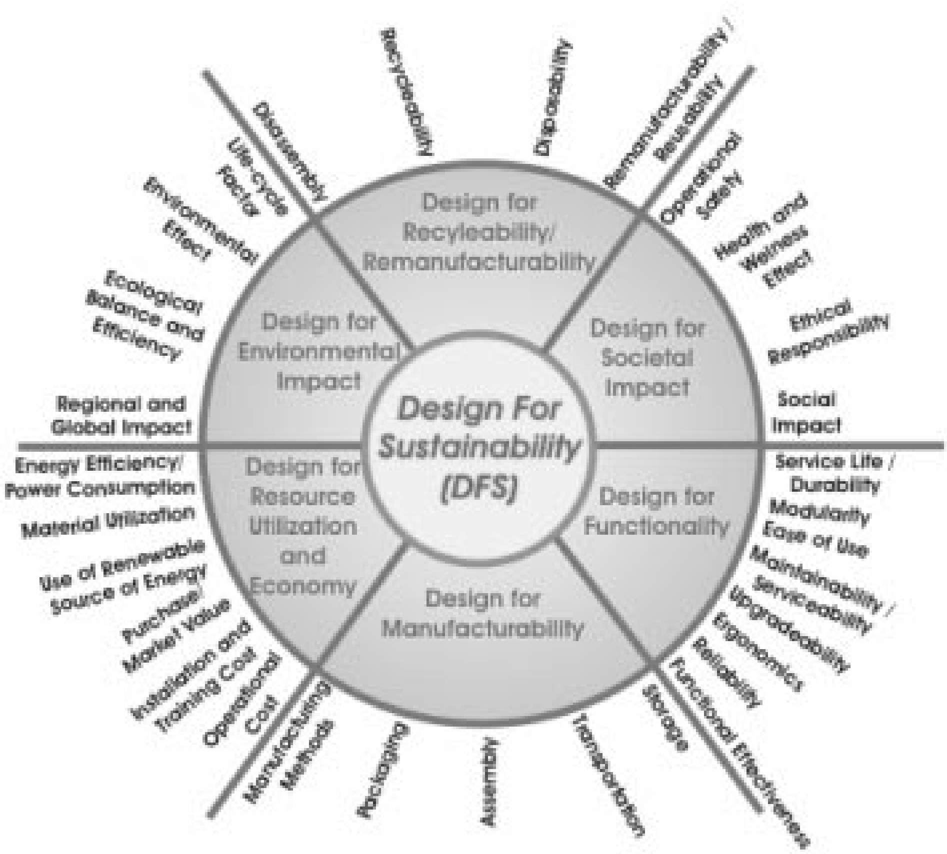


Fig. 3. Integral elements of design for sustainability.

be performed irrespective of the 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 bolt is considered, it goes through a few clearly defined production stages; bolt 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 even though these processes either directly or indirectly contribute to it. 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.

*1) Energy consumption*

Measured during manufacturing operations to observe the power consumption level and this can be evaluated against the theoretical values to calculate the efficiency of the power usage during the operation. Significant work has been done in this area to monitor the power consumption rate and to evaluate energy efficiency.

*2) Manufacturing cost*

Optimal use of machines and tooling including jigs and fixtures can provide reduced manufacturing costs. Limited analytical and empirical models are available for this evaluation, but accurate calculations are highly complex and would require customized applications.

*3) Environmental friendliness*

Basic factor contributing to environmental pollution can be one or all of emissions from metal working fluids, metallic dusts, use of toxic materials, combustible or explosive materials. Compliance with the US Environmental Protection Agency (EPA) [36], Occupational Safety and Health Administration (OSHA) [37], and National Institute for Occupational Safety and Health (NIOSH) [38] regulations are required. Measurable parameters have been defined, and these measures are continually updated. Issues of major concern in environmentally benign manufacturing are presented in a major study involving international organizations and their practices [39].

*4) Operational safety*

The amount of unsafe human interaction during a manufacturing operation and the ergonomic design of the human interface are in focus for this category. Also, compliance with regulatory safety requirements is made mandatory. Statistical data on safety violations and the associated quantifiable corrective measures are usually being reviewed and updated.

*5) Personnel health*

Compliance with the regulatory requirements according to EPA, NIOSH and OSHA, on emissions from manufacturing operations and their impact on directly exposed labour can be the basis for this category of assessment.

*6) Waste reduction*

Recycling and the disposal of all types of manufacturing wastes, during and after the manufacturing process, are accounted for in this category. Zero-waste generation and hazard-free ejection into the environment are among the most emerging research topics. Scientific principles are still emerging with powerful techniques such as lean principles being applied, in quantifiable terms.

The basic driving force in sustainability studies as it applies to manufacturing processes is the recent effort 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 develop it up to the 'level of acceptance' for common practice in industry. This can be achieved in different stages. First, in the characterization stage, the most important measures of the rating system for manufacturing process sustainability must be identified and established through literature, in-house/field surveys and appropriate experimental work. Shown in Fig. 4 are some of the key parameters that can be considered typically in a machining process [35].

These observations and existing modelling capabilities will then be used to model the impact of the manufacturing process on the contributing major sustainability parameters. A hybrid model-

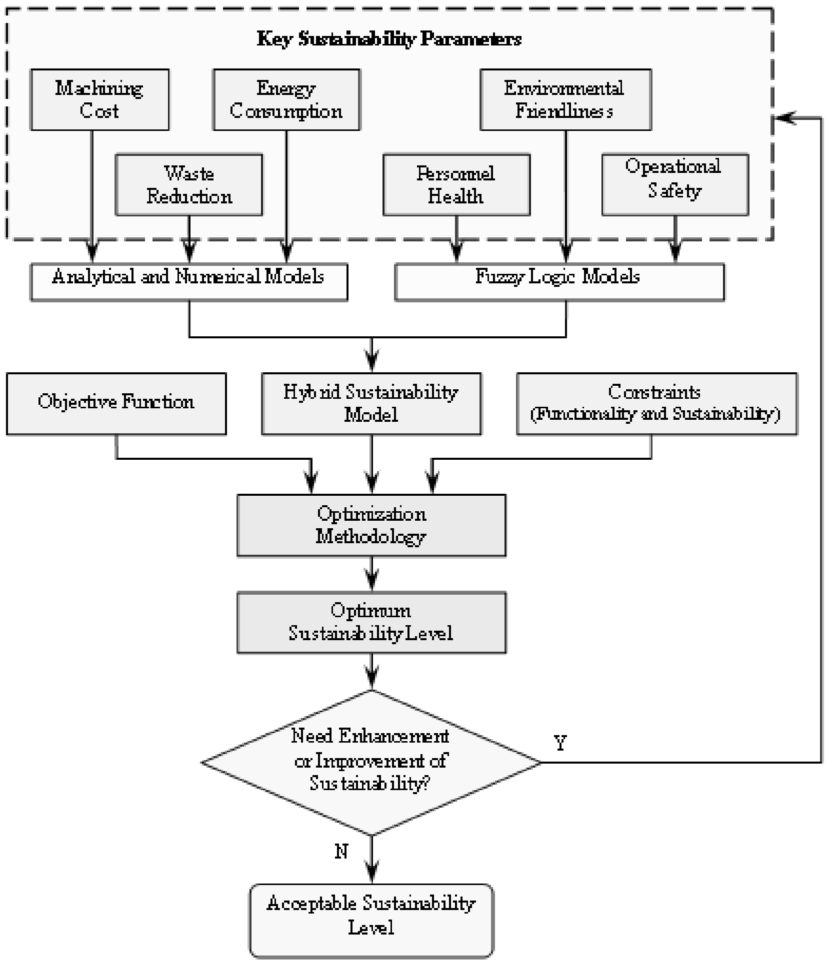


Fig. 4. Sustainability evaluation of manufacturing processes [34].

ling technique involving analytical and numerical methods, coupled with empirical data and artificial intelligence techniques must be developed to scientifically quantify the influence of each parameter. Then, the modelled production process can be optimized to achieve a desired level of sustainability with respect to constraints imposed by all involved variables. These optimized results can then be used to modify existing processes and enhance the manufacturing performance with respect to the main factors considered [40].

Finally, the optimized results can be used in defining the sustainability rating for the specific manufacturing process. In establishing this final sustainability rating, weighing factors can also be used to bring out focused evaluation and to serve the customized application.

*Systems perspective for sustainability*

The manufacturing systems planning aspects of processes, process logistics and the overall infrastructure would be needed for design and manufacture of products. In the context of sustainability, it is expected that the overall manufacturing system becomes sustainable in order to provide required sustainability support for the entire production cycle. Over the years, several technologically advanced manufacturing system concepts have emerged with tremendous capabilities for high productivity in the manufacture of high quality products at low cost. Unfortunately, these advances have not yet been adequately embraced. Product and process sustainability concepts within the application boundaries, have been developed with only the exception of lean manufacturing techniques which are primarily aimed at waste minimization and improved system logistics to provide greater productivity, an aspect which is included in our sustainability concepts for products and processes. Also, sustainable quality systems including the self-learning and human-based methodologies that pose significant variability in product and process quality need to be devised and implemented. Sustainable manufacturing systems of the future will be comprehensive systems facilitating the overall logistics needed for sustainable manufacture of sustainable products.

There is a need for developing sustainability criteria for manufacturing systems to represent the level of sustainability built in the manufacturing system by taking into account several major contributing factors including the following:

1) waste minimization (inventory levels);
2) human-machine interfaces and their interactions;
3) manufacturing costs;
4) maintenance of machines and equipment;
5) production flow and cycle time factor;
6) predictable product and process quality;
7) agility/reconfigurability of the manufacturing system.

## PROPOSED CURRICULUM DEVELOPMENT

The proposed curriculum in sustainability engineering is based on the strength of partnership among the three major participants: university, industry and state and federal organizations. 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 as shown in Fig. 5.

Traditional educational programmes are evolved around the need for educating engineers and scientists with 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. The new curriculum will focus on multi-disciplinary, interconnected and environmentally and societally-relevant subjects knitted together to form the fabric of 'sustainability engineering'. Significant emphasis will be placed on developing appropriate models for various elements such as environment, economy, societal benefits, etc., along with a thorough understanding of the natural cyclic systems representing the biocomplexity and reusable material bases including recyclability of materials. Design for sustainability principles will be taught to cover all relevant elements of practical sustainability such as disassembly, recovery, reuse, safety and maintenance of products and processes. Also, the significance of marketing, innovation, management, ethics, regulations, etc., will be covered in this proposed approach to provide a much broader knowledge base for next generation design engineers as shown in Fig. 6.

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 Ph.D. is shown in Fig. 7.

The fundamental difference between this proposed method and the current methods is that

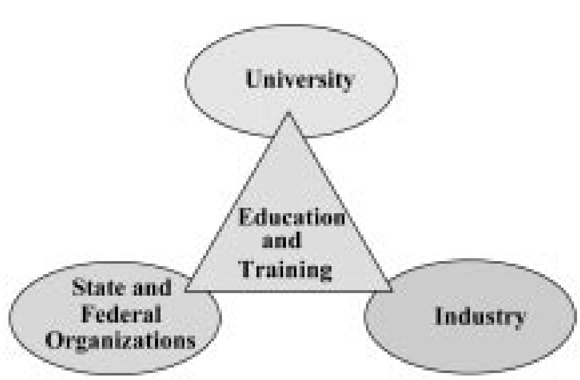


Fig. 5. Strategic partnership for education and training.

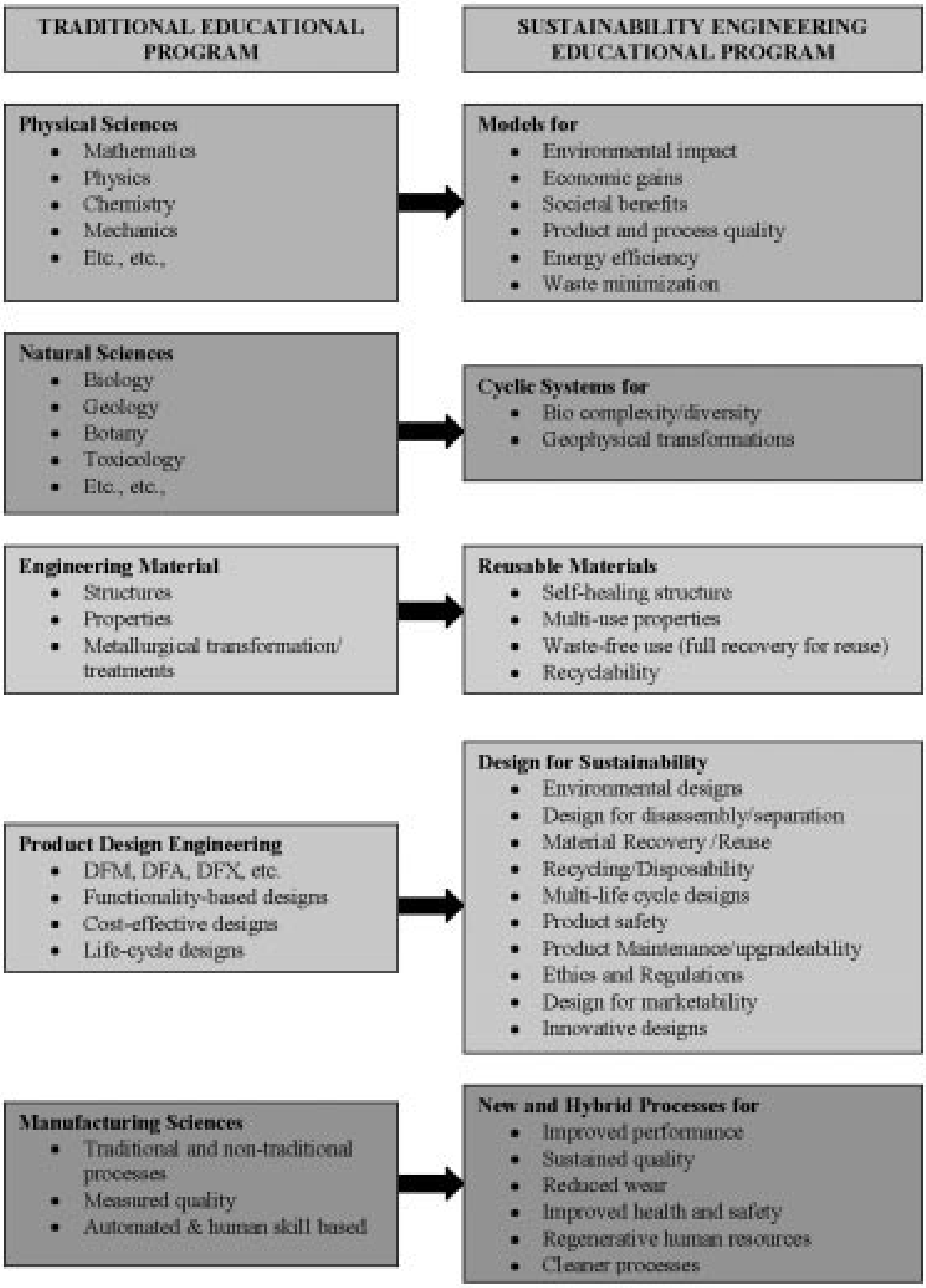


Fig. 6. Paradigm shift for sustainability engineering education.

the role and responsibility of engineers and the history of product development as it evolved over centuries to empower human civilizations is emphasized in Year 1 of the undergraduate curriculum. Also, in Year 2, undergraduates will learn industrial growth elements, technological innovation and workforce development needs. Academic learning of sustainability principles in product design and manufacture begins in Year 3 with students undertaking industry-based projects and being involved in industrial outreach programmes. M.S. and Ph.D. programmes are proposed to focus on basic and applied research, model development for sustainability applications in products and processes and industry-based project work including internships in industry.

The proposed curriculum is an extended programme beyond the traditional degree programmes shown above. Fig. 8 shows the five basic elements of this curriculum structure featuring:

1) a new curriculum based on instruction, lab work and projects at undergraduate and graduate levels;

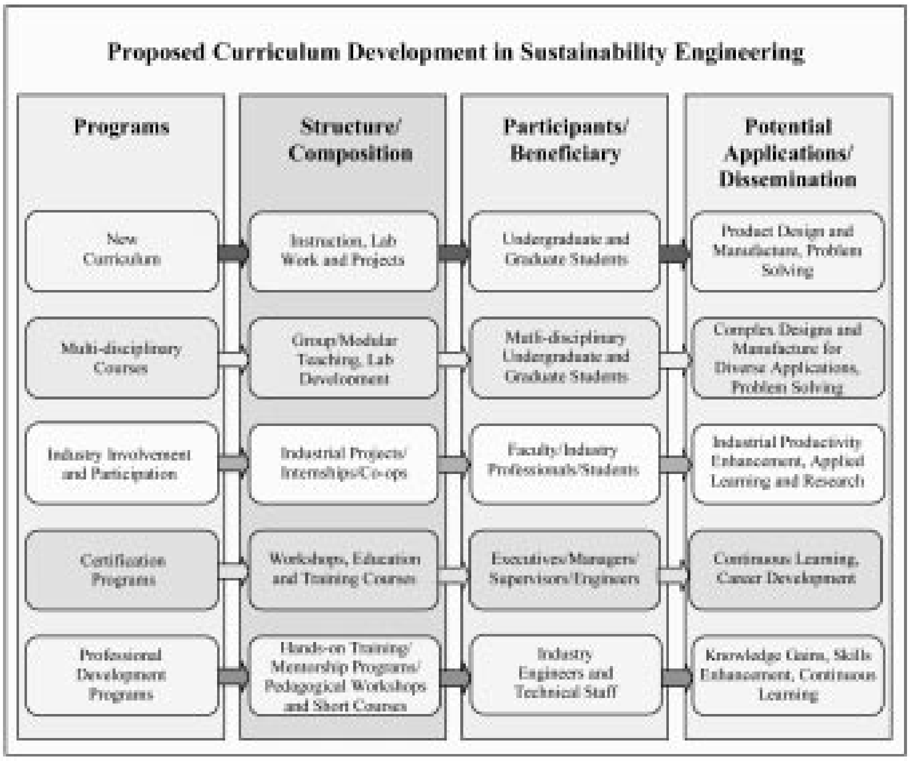


Fig. 7. Basic elements of proposed curriculum.

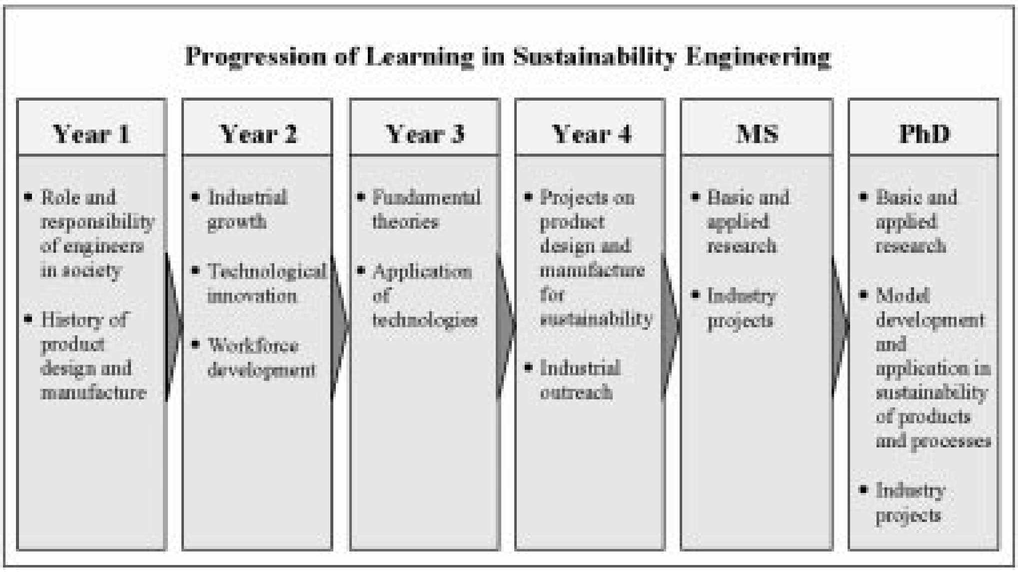


Fig. 8. Progression of cumulative academic learning in sustainability engineering.

2) multi-disciplinary courses in the current curriculum to provide a broader perspective on sustainability;
3) industry involvement and participation;
4) certification programmes for engineers working in industry;
5) professional development programmes such as short courses.

## CASE STUDY

*Developing and implementing a new graduate course on sustainable products, processes and systems*

A recent effort to introduce a new course on sustainable products, processes and systems at graduate level within the current structure of the

Masters degree programme in Manufacturing Systems Engineering at the University of Kentucky is summarized below. This course was developed and implemented by a group of seven faculty and three technical staff from the university, with participation from a few local industry groups representing the automotive, consumer electronics and equipment manufacturing segments of manufacturing industry.

A range of topics relating to sustainability in design and manufacture was covered through specialized lectures in class by the participating faculty. This included:

- Fundamentals of sustainable products, processes and systems;
- Product life-cycle design and manufacture;
- Products assembly and disassembly methods;
- Product and process design for environment;
- Product design and manufacture for functionality;
- Engineering economics for sustainable manufacture;
- Safety and ergonomics for sustainability;
- Organizational structure for sustainable systems;
- Societal aspects of sustainability;
- Technical communication;
- Professional ethics.

These lectures also included several case studies drawn from automotive, aerospace and consumer electronics product design and manufacture and specific sustainability applications.

The students were divided into four project groups and assigned with industry-based projects requiring sustainability improvement in product design and manufacture. Product and process innovation was an expected element of the project. Each project group was jointly advised/supervised by a faculty and a senior engineer from the industry. Students were able to demonstrate the economic, environmental and societal benefits, in some quantifiable terms, from the project outcomes. Course evaluation was made as follows:

- Project Plan (Week 3)
  10% (Team work)
- Progress Reports (3) (Week 5, 9, 12)
  30% (Individual effort)
- Mid-term Presentation
  10% (Individual effort)
- Final Report and Presentation (Finals Week)
  50% (Team work)

## CONCLUSIONS

We have highlighted the need for significant changes in the traditional curriculum for product design and manufacture to accommodate basic sustainability principles, beyond the well-known life-cycle analysis, and their applications. Sustainability evaluation methods are shown for manufactured products and manufacturing processes, along with a systems perspective for sustainability applications in manufacturing organizations. The proposed new curriculum provides a structure for undergraduate and graduate education, multidisciplinary courses, industry involvement and partnerships, certification and professional development programmes for industry-based engineers.

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