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A LEXICON OF GREEN ENGINEERING TERMS

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ABSTRACT

Environmental concerns play an increasingly important role in product and process design. As these concerns have mounted, so has the research effort into ways to reduce the environmental impact of products and processes. In this paper, a survey of the current research effort is given, examining some general approaches to negative environmental impact reduction and their goals. The general approaches discussed include sustainable development, industrial ecology, life cycle design, green engineering, design for the environment, environmentally conscious design and manufacturing, pollution prevention and environmental engineering. The scope of environmental concerns and the scope of temporal concerns are introduced to distinguish the domain of each approach.

INHALTSANGABE

Sorgen um die Umwelt spielen eine immer wachsende Rolle in der Konstruktion neuer Produkten und Prozessen. Gleichfalls hat die Forschung in der Reduzierung der Umweltschaden dieser Produkten und Prozessen zugenommen. In diesem Artikel wird eine Übersicht der heutigen Forschungsbemühungen gegeben worin einige algemeine Methoden zur Umweltschadenreduzierung und ihre Zielsetzungen untersucht werden. Die Diskussion bezieht sich auf die folgende Methoden; “sustainable development, industrial ecology, life cycle design, green engineering, design for the environment, environmentally conscious design and manufacturing, pollution prevention and environmental engineering.” Die Bereicher der Sorgen und Zeitspannen wirden introduziert als Grundlagen für die Unterscheidung des Domänes jeder Methode.

1 INTRODUCTION

In [1], technology is defined as the “transformation of our natural and symbolic (information) environments by human behavior.” Engineering involves the creation of technology, and therefore transformation of the environment. In this article, Devon argues that the transformations of the environment due to technology have increased in scale to the point that environmental considerations are necessary during the design of that technology.

Research into methods and techniques in environmentally conscious engineering has grown tremendously in the past ten years. Those involved in this work at some time or other have witnessed contentious semantic discussions about just what is or is not considered “environmentally conscious”. Within the area of pollution prevention, for example, the emotional debate over whether or not some forms of out-of-process recycling are considered prevention has divided practitioners into camps [2]. The common thread linking all environmentally conscious engineering efforts is the goal of reducing the negative environmental impact of products during its entire life cycle, from initial design to disposal or recycling. The goal of this paper is to characterize the major initiatives in environmentally conscious engineering, and identify their similarities and differences in terms of the scope of environmental and temporal concerns.

The general goal of environmentally conscious approaches is this reduction of the impact of a product throughout its life cycle. Two general approaches exist. The first approach takes this goal to its logical, albeit impossible, extreme. If the environmental impact of a product life cycle can be reduced to zero, the cycle would be *absolutely* sustainable, and the product could be designed, manufactured, used, and disposed of without affecting the environment. With the Second Law of thermodynamics indicating the infeasibility of achieving this, the emphasis in this approach is in creating a product cycle which is as sustainable as possible. The second approach notes that there is a certain amount of negative impact from a current cycle, and measures success based on the *relative* reduction of this impact, or the “cleaning” of the product cycle.

According to Webster’s [3], to sustain is “to maintain, keep in existence, prolong.” The sustainability of a system can be taken to be the ability of that system to be maintained or prolonged, so that a completely sustainable system could be (theoretically) maintained forever. In the context of the work discussed here, complete sustainability can be expressed as having no impact (*zero-impact*) on the environment. In the Call for Action of the “Preparing for a Sustainable Society” conference [4] the participants note the need for sustainability, stating that efforts should be directed towards “[Creation of] a sustainable , world-wide, economic community which ... reduces abuse of the biosphere and of society.”

“A *cleaner technology* is a source reduction or recycling method applied to eliminate or significantly reduce hazardous waste generation” [5]. The general approach, as noted above, is one of reducing the negative impact of a product life cycle with a focus on hazardous materials. If the cycle were to be sustainable indefinitely, there could be no input of material and energy, and no output of waste. The ideas of cleaner technology, or more specifically cleaner production, represent the need to become more sustainable along the way to complete sustainability. Indeed, Tipnis, in his discussion of sustainable growth [6], discusses reduction of impact rather than the more stringent complete sustainability.

2 DIFFERENCES IN THE SCOPE OF CONCERNS

As the importance, and economic benefits, of environmentally conscious engineering have become apparent, research into methods and techniques in this area has grown tremendously. Unfortunately, the terms and definitions used to describe these efforts have grown as well. The variety of terminology employed by researchers has made it difficult to identify the areas of greater concentration, and thus has reduced cooperation. In this section important approaches to reducing environmental impact are identified and classified according to the scope of concerns addressed within each approach.

Several general approaches to reducing negative environmental impact were identified through literature search, where we define an *approach* as a guiding philosophy. These are: environmental engineering, pollution prevention, environmentally conscious design and manufacturing, design for the environment, life cycle design, green engineering, industrial ecology, and sustainable technology.

We have used two basic factors to distinguish the approaches, namely:

- *Scope of Environmental Concern.*: What impact is considered by each approach? The impact being considered may be as narrow as the impact of the emissions from a single manufacturing plant, or as broad as the total impact from all material extraction, processing, use, and disposal operations of all industries in the world.
- *Scope of Temporal Concern*: What is the time scale over which the impact mentioned above is considered? Possible considerations range from the impact during only the manufacturing process to the impact until the earth crashes into the sun.

The approaches mentioned above were examined in relationship to these concerns and the approximate scope of both environmental and temporal concern was determined, as will be discussed in Section 3. These scopes were plotted as shown in Figure 1 to illustrate the domain of each approach. While the limits mentioned serve to define the possibilities for the scope of environmental and temporal concerns, some important gradations within these ranges are necessary to demonstrate the differences in the approaches. These gradations were based on the survey of the literature and were chosen to indicate an increasing scale of concern along the axis.

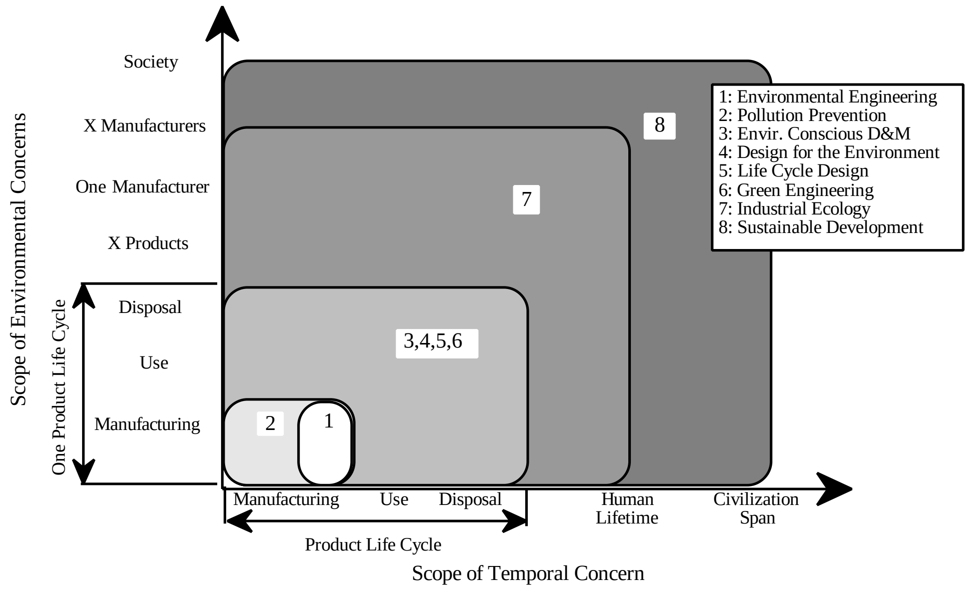

Figure 1 Environmental and Temporal Domains of the Approaches for Reducing Environmental Impact

Rather than indicate years, the temporal concern gradations were based on life spans of products, people, and civilizations. The scale as shown is not linear but instead used to indicate important distinctions between the approaches. Within a product life cycle an additional set of distinctions were made, indicating manufacturing, use, and disposal as possible lengths of temporal concerns. It is recognized that a product life cycle could be as short as 1-2 years for consumer electronics or longer than 30 years for an airplane or ship, and that the application of a given approach might change accordingly. As noted in our conclusions, the effects this variation in life cycle scale will be addressed in future work.

Similarly, the scale of environmental concerns was chosen to indicate distinctions. These gradations are fairly self-explanatory; although it is worth noting that "X products" refers to the negative environmental impact of some number of products X, and that a scope equivalent to "One Manufacturer" would indicate concern about all the activities of a single manufacturing firm.

This figure indicates the relative domain of the approaches mentioned above. In the next section, a brief introduction to these approaches is provided, along with a justification for the placement in the table above.

3 GENERAL METHODS AND THEIR PROPONENTS

Eight main approaches to reducing the impact of design and manufacturing have been identified. These are: sustainable technology, industrial ecology, life cycle design, green engineering, design for the environment, environmentally conscious engineering, pollution prevention, and environmental engineering. In this section each of the approaches is briefly defined. In addition, the intent of the various methods are discussed, and representational references to the literature are provided. These approaches are organized from the smallest scope of concerns (environmental engineering) to the largest (sustainable development) as shown in Figure 1.

3.1 Environmental Engineering

Environmental engineering is concerned with managing the fate, transport, and control of contaminants in water supplies and discharges, air emissions, and solid wastes. In the manufacturing context, the focus of environmental engineering effort is after pollutants have been generated, or at the "end of the pipe". As U.S. environmental policy expanded from clean water to clean air to cradle-to-grave solid and hazardous waste management, environmental engineering research helped us better understand how pollutants migrate through soils, groundwater, and the air, and developed treatment technologies to minimize their impact on the natural and human environments. Over the past 30 years, treatment and disposal technologies (stack scrubbers, clarifiers, incinerators, synthetic landfill liners, etc.) were codified in technology-based policies and incorporated into manufacturing processes. One problem with traditional environmental engineering approaches is intermedia transfers. Pollutants removed from the air using stack scrubbers are transferred to wastewater, which is then treated. The end result is a solid or hazardous waste sludge that may still contain the original air pollutants. The sludges require further treatment, either dewatering or incineration, prior to disposal in a regulated landfill. An effective NIMBY (Not In My Back Yard) response to the rising demand for landfill space brought industry and policy makers to their senses. The long term approach to reducing environmental impacts should focus on changes in the products and processes themselves---before the end of the pipe.

3.2 Pollution Prevention

As the U.S. hazardous waste regulations were implemented in the early 1980s, the concept of pollution prevention, as an alternative to treatment and disposal, was embraced by pioneering corporations (for example the 3M Company) and state-level industry assistance programs. Subsequent amendments to the regulations established a hierarchy of preferred waste management approaches: source reduction, closed-loop or in-process recycling, out-of-process recycling, treatment, and disposal. The Pollution Prevention Act of 1990 narrowed the range of activities to those that eliminate pollutants altogether: equipment, technology, process, or procedure modifications; reformulation or redesign of products; substitution of raw materials; and improvement in management, training, inventory control, materials handling, or other general operational phases of industrial facilities [7]. As practiced in industry, pollution prevention usually focuses on elimination of pollutants from existing products and process technologies [8]. The transition from pollution control to prevention has been hampered by limited information, technologies and capital, as well as by impediments in existing regulatory policies [9].

3.3 Environmentally Conscious Design and Manufacturing

Perhaps the most recent approach to emerge is that of environmentally conscious design and manufacturing(ECDM). ECDM can be divided into environmentally conscious product design and environmentally conscious process design, or environmentally conscious manufacturing (ECM). Rather than designing *for* the environment, the philosophy of ECDM recognizes that there will be negative environmental effects from the product life cycle, but that the designers are conscious of this during the design. An overview of this work can be found in [10], which notes that it is important to include "*every* operating constraint into the initial design phase of the product or process life cycle." Implementations of ECM are noted in [11] and in fact most of the *Journal of Environmentally Conscious Design & Manufacturing*.

ECDM is quite similar to the next few approaches discussed. In each of these approaches, the scope of considerations, both in terms of time and the environment, is the life cycle of one product. Environmental concerns include all phases of this life cycle, extending beyond the scope of pollution prevention to include the negative impact resulting from the use and disposal of this product. Similarly, the time scale considered is that of the product life cycle, from design and manufacturing through use and final disposal or recycling of the materials in the product.

3.4 Design For The Environment

From the U.S. EPA's Design for the Environment Fact Sheet (1993):

> "As it is generally used, the term 'Design for the Environment' (DFE) means making environmental considerations an integral part in the design of a product, process or technology. The concept of DFE originated from industry's efforts to target specific environmental objectives for design engineers to incorporate when creating a new product."

Design for the environment is somewhat of a misnomer, since true DFE would be to reduce the impact to zero by not designing it at all. The idea of DFE is instead that the environment be *considered* during the design process. The EPA's involvement in this can be seen in [12], which discusses the U.S. EPA's work, unfortunately without ever suggesting a definition for DFE.

In [13, 14] a general overview of Design for the Environment can be found. The work of Olesen and Keldmann[14] is particularly interesting as a general overview of design methods considered to be part of DFE. Navin-Chandra [15] mentions DFE in a similar context, however, he immediately proceeds to use the term green engineering throughout the paper, an indication of the change of terminology mentioned in Section 3.6. Additionally, Bor and Kant [16] present life cycle analysis as a specific technique within DFE, and the survey of Van der Horst and Zweers [17] is presented within the framework of DFE. The scope of this approach is virtually identical to that of ECDM, with the span of environmental concern again being the entire product life cycle.

3.5 Life Cycle Design

A life cycle approach is described as a systematic "cradle to grave" approach and "provides the most complete environmental profile of goods and services"[18]. The argument is that consideration of the entire life cycle helps designers "ensure that the environmental impact of their products are discovered and reduced, not merely shifted to other places." As such, the scope of this approach is again one product life cycle, both temporally and environmentally.

As stated in the U.S. EPA's Life Cycle Design Guidance Manual, the primary objective of life cycle design is "to reduce the total impacts and health risks caused by product development and use." [18] This is accomplished by examining the environmental impact of the activities related to each stage of the product life cycle, from material acquisition to disposal. This makes it possible for designers to recognize that a slight reduction in waste during production may result in greatly increased waste at disposal. Since the *total* impact is to be minimized, each stage must be examined. While the U.S. EPA is one of the most important proponents of this philosophy, they are by no means alone in their support. In [19], Alting and Jørgensen present life cycle design as a basis for sustainable production, relating this approach to goals mentioned above. Alting and Jørgensen also provide references to other work in their paper.

It should be noted that the roots for Life-Cycle Design can be traced to the early seventies when the U.S. Defense Advanced Research Program Agency (DARPA) initiated investigations in so-called Unified Life-Cycle Engineering (ULCE), see, e.g., [20], followed by research in Concurrent Engineering (CE) and, more recently, Integrated Product and Process Development (IPPD). CE is defined as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacturing and support. It is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements" [21]. Some consider the more recent IPPD to be an expansion of CE because it focuses on the integration of products and business processes. Experience tells that this may be another phrase incorporating the same ideas as CE. Many use CE and IPPD in a narrower definition and see both as specific design techniques emphasizing teamwork in design and manufacturing. Keoleian and Menerey [18] discuss the use of CE in life cycle design and note that CE is usually used to improve product quality and manufacturability. CE and IPPD can be viewed as the roots for the U.S. EPA's life-cycle design approach, though the U.S. EPA places higher emphasis on environmental issues than traditional CE and IPPD.

3.6 Green Engineering

From the U.S. Congress Office of Technology Assessment [22] "green design involves two general goals: *waste prevention* and *better materials management*." This is one of the more limited definitions. For instance, in [15] Navin-Chandra defines green engineering as "the study of, and an approach to, product/process evaluation and design for environmental compatibility that does not compromise product quality or function." In the U.S., it is presented as the successor to DFE, encompassing many of the same tools. Navin-Chandra remarks that highly focused approaches such as design for recyclability may be too narrow, noting that while thermoplastics are easier to recycle that thermosets, thermoplastics are not as strong and an increased volume must be used, possibly negating any environmental benefit from increased recyclability.

3.7 Industrial Ecology

In industrial ecology, a much larger scope of concerns is applicable. While the previously discussed approaches were limited to a single product from a single manufacturer, the concern of industrial ecology ranges over many products from multiple manufacturers. In addition, this approach is not limited to a single product life cycle, instead considering the interactions of several product life cycles (of possibly different lengths) over a larger time scale.

This term was popularized by an article by Frosch and Gallopoulos [23]. In this article, the idea of an industrial ecosystem is introduced to take advantage of the analogs to biological ecosystems. They note that this ecosystem would ideally be closed: "a chuck of steel could potentially show up one year in a tin can, the next year in an automobile, and 10 years later in the skeleton of a building." For this closed system to exist, any waste from one part of the ecosystem must be used as input to another part of the system. Using this idea, waste from one manufacturing process does not have a negative impact on the environment if it can be used as input to another process. “Some manufacturers are already making use of 'designed offal' or 'engineered scrap,' in the manufacture of metals and some plastics: tailoring the production of waste from a manufacturing process so that the waste can be fed directly back into that process or a related one.”[23]

Frosch (with M. Uenohara) in [24] writes:

> *Industrial ecology* provides an integrated systems approach to managing the environmental effects of using energy, materials, and capital in industrial ecosystems. To optimize resource use (and to minimize waste flows back to the environment), managers need a better understanding of the metabolism (use and transformation) of materials and energy in industrial ecosystems, better information about potential waste sources and uses, and improved mechanisms (markets, incentives, and regulatory structures) that encourage systems optimization of materials and energy use.

Industrial ecology serves as a general paradigm for "improving the environmental performance of industrial processes and the environmental attributes of products" [24]. Within this paradigm, a variety of techniques for accomplishing this improvement can be found. As chronicled in [24], areas of concern include energy use, material consumption, impact evaluation, design for environment, and recycling.

3.8 Sustainable Development and Technology

The most general approach noted in terms of scope is sustainable development and technology. The most common definition is taken from the United Nations’ World Commission on Environment and Development, and specifically from their report *Our Common Future*. Sustainable development is defined as “development that meets the needs of the present generation without compromising the needs of future generations.” In a similar vein, Georgia Tech’s Center of Sustainable Technology uses the definition: “sustainable technology is the finding of practical solutions to achieve economic growth in harmony with the environment.”

The concern of sustainable technology is the impact of all human activity, and the time span considered is essentially the life of the planet. This approach is remarkable for its inclusion of economic growth within the stated goal, and for the sheer scope of the concerns. As such, some of the approaches mentioned above have been implemented as part of a sustainable development concern presented by Hatch at the World Partnership for Sustainable Development (WEPSD). He noted that achieving sustainable development requires "pollution prevention, consideration of life-cycle consequences of production, and an approach that imitates natural or biological processes..." This provides at least an indication that an effort is being made to integrate these approaches and take advantage of the strengths of each.

4 CONCLUSIONS AND FUTURE WORK

The mapping presented in Figure 1 represents a work in progress. There are a number of more focused approaches, for example design for assembly, service, or recycling, that have not yet been examined and placed on this map. As our work continues, these will be incorporated. We noted in Section 2 that the scale of temporal concerns was based on a product life cycle, inclusion of (and distinction between) many of the more specific approaches will require inclusion of product life cycles of various lengths. For example, design for serviceability is rarely a concern for consumer electronic components, since the expected life is short, but is an important concern for the design of airplanes and ships which are expected to last 30 years or more.

In the U.S., there is increasing pressure to focus publicly funded research to meet broader social goals. The particular champions of the various approaches discussed in this paper appear to be from a wide variety of academic disciplines and organizational contexts. In this initial paper we have presented a framework for broadly characterizing, comparing, and contrasting the various research and development activities considered environmentally conscious or “green”. The effort summarized in this paper will be augmented with additional information on the intellectual leaders and the objectives, scope, and status of their specific research programs. This information will be used to facilitate the development of unified research strategies and foster cross-disciplinary learning.

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