Postponing Product Retirement through Engineering Design

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Abstract

The environmental impacts of a product can be reduced in the three phases of its life cycle: production supply chain, service and retirement. The reduction of production volume, especially by extending the service life of existing products would mitigate environmental impacts. Durability, maintenance and repair can prolong normal operation. However, if service requirements change, the product may be retired while still in working condition. In these cases, retirement could be postponed if the product is capable of “adapting” to the new requirements. This paper shows the scope of “postponing retirement” in environmental design research, and discusses the benefits of adaptable design.

Keywords: Product Obsolescence, Product Retirement, Adaptable Design, Life Cycle Design

1. Introduction

Increasingly, public awareness and concerns about environment and natural resources have demanded practices of sustainable development from all sectors of society. Product manufacturing enterprises that had traditionally been concerned with quality, cost and development time of products must also consider the negative impacts of products on the environment during their life cycle. Thus, in addition to traditional criteria of products such as quality, features, cost and delivery time, environmental impact has also become an important criterion for both public responsibility and potential legal liability.

To assist analysis of product life cycles, a discrete product such as automobile may be considered having three phases of life cycle in terms of the physical product existence: creation (through production), operation (usage) and post retirement. Reduction of environmental impact may be achieved in all three phases of a product's life cycle. In comparison with

life cycle environmental methods, a fundamentally different approach is the reduction of production volume, while meeting society's demands for products. This requires that a fundamental change occur in society's value system –encouragement of preservation, conservation and technical advancements to provide the required functions/services with fewer products. Postponing retirement of a product is one way to accomplish this production reduction. Products are kept in service longer, resulting, in the long run, in the consumption of fewer products.

Product retirement can happen for two reasons. First, products can no longer satisfactorily deliver their expected functions due to damage, wear, aging, etc. Second, the current operation of a product may no longer be desired, even if the product is in good working condition. This can be caused by changes in customer requirements, working environment or regulations, or by the technological obsolescence of some product parts, etc. In the former case, product retirement may be postponed by making high quality products that are durable, and easy to maintain and repair. These characteristics are primarily determined by product design and, then, by the quality of material and production. In the latter case, retirement may be postponed only if the product can be adapted to the new service requirements. This generally requires some form of alteration or modification of the product, termed “adaptation”. The ability of a product to facilitate adaptation depends primarily on the design of the product.

This paper discusses the general idea of sustainable development and its implications in product design and production. It, then, reviews the spectrum of approaches to environmental design and shows the scope of “postponing retirement” within this spectrum. Adaptable design is introduced as a method to extend the service of products. The criteria for its

applicability in various design problems are given, followed by conclusions at the end of the paper.

2. Sustainable Development

Currently, economic growth is still dominated by mass production and mass consumption of products. The negative side of this growth is the decrease of resources and irreversible environmental damage, which is evident by various phenomena such as global warming, thinning of the ozone layer, levels of air and water pollution, volume of landfills, deterioration of natural ecosystems, extinction of some species, and the gradual depletion of various resources. Thus, sustainable development (SD) is urgently needed and must be practised in all parts of the world and by all sectors of society.

Another reason concerning the urgency of the sustainability is that advanced technological abilities and machine power have extensively exploited natural resources everywhere, from mountain tops to ocean floors, in the mass transformation of these resources into products that are consumed by an increasing population. The high rates of mass production and mass consumption have resulted in a scarcity of both natural resources and the absorptive capacity of natural sinks for recycling pollution and waste [Mebratu, 1998].

Further, the supply chain has been global for a long time. Therefore, the scarcity of a resource in one place adds to its global scarcity via the spread of demand, and the traditional remedies of migration and procurement have become inapplicable. The global nature of environmental problems requires the collective effort of many nations, making the problems more difficult to solve.

Alarming signs of environmental impact, the tremendous rate of consumption, and global scarcities are among reasons that the scientific consensus, on the occurrence of ecological imbalances, has agreed that the damage inflicted by human activities on the natural environment render those activities unsustainable (Ekins and Jacobs, 1995). This has created a need for a new worldview to serve as a basis for global consensus, which eventually led to the coining of the term “sustainable development” [Mebratu, 1998]. Any sustainable development must deal with three fundamental elements: society, the environment and the economy.

2.1. Balancing the Rates

Responses to the question of sustainable development vary within a spectrum of two polarized variations [Mebratu, 1998]. At one end of the environmental debate spectrum is the “Limits of Growth” school, advocated by such groups as the Club of Rome, which projects a pending environmental crisis, to be faced by humanity. They argue that society has gone into a state of being beyond limits without knowing it. This means that the consumption “rate” has exceeded the rate at which renewable resources can renew themselves, the rate at which we can change from nonrenewable resources to renewable ones, and the rate at which nature can recycle the pollution. They warn about the overuse of such crucial resources as food and water while overwhelming nature with pollutants like those causing global warming ([Meadows et al., 1992], [Bhaskar and Glyn, 1995]).

At the other end of the spectrum are the technocrat/economist optimists, exemplified perhaps by parts of the World Bank’s World Development Report, who argue that resource constraints can be overcome at relatively little cost, provided the correct (usually market-oriented) policies are put in place [Mebratu, 1998].

Despite different views on the severity of environmental problems, there is agreement on a general principle, which is based on the fact that for the long-term sustainability of any finite system, the input and output rates have to be equal. This principle concerns the necessity of a balance between the consumption rate and nature’s renewal capacity.

Figure 1: Natural Tap and Natural Sink

Figure 1 shows a simple view of the above discussion. The natural renewal mechanisms of the environment are depicted as our planet. These mechanisms provide a natural tap, which supplies resources, and a natural sink, which absorbs the waste and pollution that we create. They both have limited capacities. In light of this view, for long-term sustainability of the environment, the rate at which resources are consumed has to be within nature’s supply capacity, and the rate

at which society generates waste and pollution has to be within nature's absorption capacity. This balancing act is the general principle of SD.

2.2. Environmental Impact (EI)

For the purpose of analysis, the depletion of resources may be treated as environmental damage similar to pollution (although they are different). On the other hand, the capacity of natural sinks can be treated as a resource, thus allowing us to treat pollution as resource consumption. This treatment facilitates the use of a general term, Environmental Impact (EI), to refer to both consumption of resources (utilizing the tap) and pollution of environment (utilizing the sink). Several EIs can be identified such as material and energy consumption, water pollution, air pollution, solid waste and ecosystem toxicants. These EIs can be measured based on various criteria in the environmental assessment of products, for example global warming, ozone depletion, ecotoxicity and human toxicity, and resource consumption [Hauschild and Wenzel, 1998]. Using this term, we may rephrase the general principle of SD as: *"The rate of society's EI has to be less than or equal to nature's renewal capacity"*.

3. Reducing EI of Products

Various criteria have been developed to measure the reduction of EIs in design and production engineering. For example, Rivera developed seven criteria to measure environmental consciousness: recyclability, reusability, maintainability/serviceability, emissions, energy consumption, materials, and durability [Rivera and Lin, 1999]. The study of these and other criteria reported in literature reveals that there are two broad approaches to the EI reduction of products. The first is the reduction of EI in the processes of a product's life cycle. The second approach is the reduction of production volume.

3.1. Product Life Cycle

For the benefit of this discussion, the life cycle of a product is divided into three phases: creation (through production), operation and post retirement. The first phase includes all the activities in the product creation chain until the product reaches the end user. Examples of these activities include mining, transportation and other logistic support, extraction of raw material from ores, material processing and forming, manufacturing, assembly, packaging and shipping. The second phase is the usage of the product for its normal operation, for example driving an automobile. The third phase includes the fate of the product after it is retired, such as disposal or recycling. Reduction of environmental

impacts may be achieved at all three phases of a product's life cycle [Tipnis 1998]. An EI reduction example will be showed later of this section.

3.1.1. Production Supply Chain

Different products may undergo different processes in the production supply chain. The required materials can be obtained from virgin resources or from recycled products. Various chemical and forming operations prepare the material for the manufacturing of parts. Numerous manufacturing operations such as machining, forging, casting, chemical processing and painting may be performed, followed by assembly, inspection, packaging and shipping. Every process in the value chain involves various internal operations and flow of goods, energy and information. It also requires logistic support such as buildings, roads, vehicles, and so on. Every activity consumes resources such as energy, space and human resources. Waste and pollution are also generated during these operations. These comprise the EI of each activity.

Figure 2 shows a typical manufacturing process. The flow of goods between the processes cross the process boundaries. The internal flow of material, energy and information ultimately determine the exchange of EI between the process and the environment.

Figure 2: The EI of the Manufacturing Process

The relationship between one operation and others in the value chain can vary substantially, from a competitive supplier-buyer relationship to a cooperative management of the supply chain that can be seen in an extended enterprise [Browne et al., 1998]. From an environmental perspective, however, it is sufficient to simply represent a process in the chain by the flow of goods and the exchange of EI. The sequence of these processes comprises the production supply chain as shown in Figure 3. Figure 3 also shows the potential environmental impacts in the production supply chain.

Figure 3: EIs of the Production Supply Chain

The left half of Figure 3 shows the flow of goods between various operations via a network of logistic support including transportation, distribution, communication, and so on. The right half of the figure shows individual processes and associated EIs. Reduction of EIs must be considered, wherever possible, in the processes involved and in the logistic operations.

Lu and Gu [2003] have presented an analysis of a product's life cycle processes. The model, in addition to the production supply chain, includes recycling, repair, reuse, and so on. They utilized "process-based analysis" for the environmental assessment of products. That is, the EI of every process within the supply chain of a product is calculated (for example, on a scale of 0 to 5). These EIs are then added up to assess the total impact during production phase. The approach extends the calculation to the operation and retirement stages as well.

3.1.2. Product Operation

The operation of a product may significantly add to its EI. A common example is the smog, created by vehicles, that seriously pollutes the air in larger cities (Figure 4). Various measures have been taken by producers, especially auto manufacturers, to reduce the operation-induced EI of their products.

Figure 4: The Operation of Products Creates EI

3.1.3. Product Retirement

Technical products have a limited service life and must eventually be retired. The irresponsible discarding of a retired product could cause serious environmental damage, especially if the product contains toxicants or requires a long time for decomposition. The immediate remedy is the proper disposal of waste in landfills. However, there are better options that, if applicable, will "reintroduce" the waste into the material/resource supply chain, hence reducing the consumption of virgin material, as well as avoiding the disposal of waste in the environment. Various post-retirement remedies apply to different products or even parts of a product. These are listed below in order of priority:

1. Remanufacture: restore the product to a working state (usually by the producer or skilled persons).
2. Part salvage: remove parts and modules that can be reused in similar products.
3. Material salvage: remove and reuse material in the construction of other products.
4. Material reclamation (recycling): remove parts made of similar material and turn them into raw material via shredding, melting, and other material processing methods.
5. Proper disposal: properly dispose of components that cannot be reintroduced in the supply chain.

The key to the success of the above post-retirement activities, from both environmental and economical perspectives, is the "design for disassembly" [Harjula et al., 1996; Desai and Mital, 2003]. One particular technique is "modular design", which optimizes the clustering of components in modules for various

objectives, including part reuse and material recycling [Gu et al., 1997].

An EI reduction example was demonstrated by General Motors (GM). GM, like other auto manufacturers, has incorporated various practices to improve environmental performance of their products during the entire life cycle (<http://www.gm.com/company/gmability>). The efforts are made in their plants, vehicles, and end-of-life recovery. (Figure 5)

Figure 5: GM's Environmental Program
(Courtesy of GM)

GM has published dismantling manuals for its different product models. The use of toxic materials (for example – sodium azide in airbags, cadmium in light bulbs, and hexavalent chromium in the resin of plastic components) is reduced via alternative technologies. Extrusion and hydroforming processes reduce scrap steel and welding processes. Polymeric parts are designed for easy recovery and recycling. Fuel efficiency and emissions have been improved. Recycled materials are used in the production of components. The amount of energy consumption, emissions, chemical effluents and solid waste generated in their production facilities have been reduced. According to their website (<http://www.gm.com/company/gmability/>), global recycling rose 15 percent from 2000 to 2001, composite greenhouse gas emissions in the U.S. were reduced by 75 percent from 1990 to 2001, and total carbon dioxide emissions declined 18 percent.

3.2. Reducing Production Volume

EI reduction by decreasing production volume is fundamentally challenging as it may very well contradict current economic growth mechanisms, unless other economic activities are utilized in order to compensate the reduction of production volumes. It requires exploration of new economic activities and even a new value system for society. For a specific type of product, if it is assumed that a relatively fixed

average volume of products must be in service at a given time, production volume of this product could be reduced if products stayed in service longer. This can be called “postponing retirement” or “extension of utility (service)”. The additional economic activities must be based on value-added activities of product retirement postponement.

3.2.1. Extension of Product's Normal Service

Products may be retired due to deterioration caused by usage or aging. To increase product life, designers have the choice of either to “design out” maintenance or to “design for” maintenance [Markeset and Kumar 2001]. Design of maintenance-free products is influenced by reliability and durability characteristics on one hand, and by cost and technological limitations on the other hand. Design for maintenance requires risk analysis, study of possible failure scenarios, and making provisions for easy disassembly and repair. An example of such provisions is the assembly of parts that frequently fail in an easily detachable and serviceable module [Gu and Sosale, 1999].

The importance of achieving greater use with fewer resources has been emphasized [Willems et al., 2003]. The use of the term “adaptation” refers to maintenance, repair, remanufacturing, upgrading or downgrading, enlargement and reduction, rearrangement or modernization. All of these processes extend the usage phase of products. They point out that the adaptability of a product, as defined above, is determined primarily by the design of a product, especially its disassembly and reassembly characteristics.

3.2.2. Adaptation to New Service

Many products are discarded while still in good working conditions because normal operation is no longer desired. The most common reason is technological obsolescence. Millions of products, especially those containing electronic parts, are retired annually due to rapid obsolescence and the proliferation of new models [Rios et al., 2003]. Another significant reason is the change in the needs or expectations of the users, which can be caused by various parameters such as age, physical condition, lifestyle, and so on. Other reasons include changes in operation regulations, quality requirements or working environments.

In these cases, durability is no longer an issue because the product outlives its required service. Therefore, the product's unused service life can be utilized only if it can be adapted to fulfill new service requirements. Adaptation, however, may be very difficult or costly.

The difficulty of an adaptation task depends on the nature of the required changes, but particularly on the “design” of the product.

Traditionally, design has been concerned with quality and performance for the “normal operation” of a product. However, recent environmental concerns have motivated producers to introduce products that can be easily upgraded (such as computer systems) or customized for varying needs. Incorporating adaptability in the design of products is called adaptable design.

4. Adaptable Design

The design process begins with the definition of the requirements, and ends with the description of a product which, when materialized, can deliver these requirements. It is assumed, therefore, that the requirements are known before and during the design processes, although the designer’s understanding of the requirements usually evolves during the process. A design that can deliver the requirements is considered “successful” [Suh, 1990].

Adaptable design (AD) is a different design paradigm that incorporates the fact that the requirements may change after the design and construction of the product are completed. Therefore, it suggests a departure from the conventional design process because the success of the design in satisfying the requirements is not the only objective. The added objective is “adaptability”, which AD treats as a “requirement” in the design process. There are two important criteria to classify AD: the subject of adaptation (design or product), and the availability of forecast information. These are explained in the following sections.

4.1. Design Adaptability and Product Adaptability

As mentioned earlier, the design process generates a design (blueprints or CAD models). Subsequently, a “product” is created based on this design. Both the design and the product can be made adaptable. It is important to note that a product cannot be adaptable if its design is not. These adaptabilities need to be distinguished because they relate to two different application areas.

A design is usually an exact prescription for the creation of a product or many identical products. The same design, with minor changes, can be used to create different designs, usually in the form of variations of the original product. This is called “design adaptability”. Design adaptability results in the development of a variety of designs based on a

common adaptable blueprint. Thus, an adaptable design replaces several designs. The realization of designs into physical products is performed by the producer; therefore, design adaptability mainly concerns the producer. As an added benefit, various production processes and even manufactured parts can be shared across designs within the product portfolio. Although adaptability in the design of a product may not be of importance to the user, the similarity between the design of one product and other models makes it easier to operate various models or swap components for repair and upgrading purposes. Figure 6 shows two models of SONY video cameras that were developed based on a common platform. Design adaptability is usually achieved via the creation of platforms with standard interfaces that allow for the attachment of various modules for different functions.

Figure 6: Example of Design Adaptability

Product adaptability refers to the ability of a given physical product to be used for different requirements or for extension of its service life. The adaptation can be performed by the user, although it can also be carried out by the producers or contractors. It can be also called “user adaptability”. User adaptations include upgrading, customization and versatility, which allows for various functions by the same product. An example is the development of adaptable homes, where adaptations happen over time as the residents’ needs or lifestyles change. This structure allows for future additions, extra space for possible future use of wheelchairs, and changes in features and functions of various parts in and around the house. Adaptable design housing etiquette requires that modifications be simple to carry out, and become very cost effective when they are planned into the initial design of the house. Figure 7 shows another example, a chainsaw that can be easily adapted to perform other functions via the replacement of add-on modules that can be attached to a common platform [Gu and Slevinsky, 2003].

Figure 7: Design and Product Adaptability Via Platform/Module Design

4.2. Specific and General Adaptabilities

AD, as opposed to conventional design, develops products that may be adapted to perform different (or added) functions than their original requirements. Therefore, the designer should have some ideas on what these additional requirements might be, and design the product accordingly. In many cases, forecast information exists and is utilized, for example in the design of video cameras shown in Figure 6. This is called “specific adaptability” because the provisions in the design are made for specific adaptations that are known in advance. However, it is also possible to design products in such a way that they are generally more adaptable, even if forecast information is not available. This is called “general adaptability”.

It is possible to develop methods for specific AD to utilize available forecast information. General adaptability, however, is more difficult to accomplish in mechanical systems, where the design of components is determined not only by their logical functions but also by spatial constraints, size requirements, forms, and so on. There are, however, strategies that can increase general adaptability of mechanical systems.

Adaptation requires modification in the structure of a product. The modification may propagate throughout the product due to the connectivity of mechanical parts through both functions and constraints. Therefore, a general principle is to use a “segmented” architecture for products, so that modifications are confined within a segment. Also, segments can be developed to perform clear functions, thus increasing the similarity between the physical structure and the functional structures of a product. Further, generic forms and shapes can be utilized to allow for future modification more easily. Finally, whenever possible, the functional relationships among various segments are performed via digital and electronic interfaces to avoid highly constrained mechanical connectivity of segments.

4.3. Applicability of AD

AD of products is not only beneficial to the environment, but also to users and producers. However, AD may require more initial design time and may involve loss of optimality in certain aspects of a design. It is important, therefore, to determine how much AD is applicable to the design problem. This decision depends on certain characteristics such as the four listed below:

1. Superfluousness

This characteristic is an indication of the “unused potential” of a product and is the most important criterion in choosing AD for product adaptability. Superfluousness is a result of idle time that a product has during its operational life, as well as its early technological obsolescence. In contrast, there are products that are mainly “consumed”, such as drill bits, cutting tools, and brake pads. For these products adaptability is generally not justified, and instead durability becomes important.

2. Product Variations

An important design characteristic is the features shared with other designs that are often considered as belonging to the same family of products. Such commonalities make it possible to adapt a design from one product to a similar one, thus justifying the cost and time of an adaptable design.

Variations of a product can occur in time sequence (new models, upgrades and customization to changing needs). These variations are a result of technological advancements, improvement in the design of previous models, or changing needs. Variations can also occur in parallel (simultaneously) as in various models, similar products, and customization for different clients. Products that have a large number of variations are generally more suitable for adaptable design, especially using product modularization methods. Also, adaptable design becomes increasingly relevant for products that are functionally similar (as a whole or in the function of their components) to other products (Figure 7).

3. Environmental Impact

Products may contain materials that are hazardous or are difficult to recycle, reuse or even dispose of. The possibility of making these products adaptable to different usages must be studied. Generally, products with larger EI in life cycles yield better environmental benefits if they can be adapted.

4. Financial Significance

Product design covers a wide spectrum of products ranging from simple screwdrivers to complex space shuttles. The extent of significance may be measured by the general costs involved. The general cost means direct and indirect monies. The latter refers to financial consequences of product failure. Costs can increase if the product is massive (e.g. an oil refinery), or is produced in high volume (e.g. automobiles). The following characteristics determine the financial significance of a design problem and affect the approach to adaptable design:

- Production Volume
- Unit Price
- Capital Investment
- Development Time

High production volume justifies more initial investment in design, including the use of adaptable design techniques, to improve the fate of thousands or millions of objects after they retire. Unit price has a similar effect; and, it becomes increasingly important for massive one-of-a-kind projects such as a nuclear power plant. In such projects, both the physical product and the design knowledge generated should be made adaptable for future use (product adaptability and design adaptability). The last two characteristics, capital investment and development time, do not directly affect adaptable design but will become important when variety is involved.

4.4. Adaptation versus Post-Retirement Approaches

The post-retirement approaches of SD are based on “redirecting” the flow of used products into the production supply chain. In Section 3, they were listed in the order of priority, which is determined by the environmental benefits (as well as financial benefits). Based on the premise that all these approaches avoid the use of virgin resources, the two categories of recycling and postponing retirement can be treated the same, as with the word adaptability in [Willems et al., 2003].

Figure 8 illustrates these approaches. Along the time axis, the processes of the production supply chain occur from left to right until the product is delivered to the user. Then, there is the usage phase, followed by the “end” point, which is retirement, at the right end of the time axis. At this time, various approaches return the product to different points on the time axis. Cumulative EI is the vertical axis. For simplicity, it is assumed that it is a linear function of time. Therefore, from any point on the time axis to the end of the production chain, EI accumulates proportionally. It can be seen that the closer the start point is to the final

product, the less the EI (area of triangles). Therefore, we could list the priority of all the above approaches in the following order: durability, repair and maintenance, adaptability (and remanufacture/refurbish), part salvage, material salvage, material recycling. The least favorable approach is disposal depicted by a red line on the right. It creates landfill pollution and requires replacement of material from virgin resources.

Figure 8: Adaptation v. Post-retirement Remedies

4.5. Scope of AD

Figure 9 summarizes the discussion of various approaches to reducing EI in engineering production, and shows the scope of AD. As indicated in the previous section, the distinction between adaptable design and “redirect” approaches, particularly “part reuse”, is often difficult to make, and this is indicated by a bracket in the figure.

Figure 9: Scope of AD in EI Reduction Approaches

5. Conclusions

Products are usually retired due to deterioration of physical conditions caused by usage and aging. In these cases, retirement may be postponed by the development of high quality products that are durable and can be maintained in service for a long time.

However, as technology is advancing at increasing speed, and many products are retired due to technological obsolescence. In this case, their durability is not an issue. One remedy is adaptation to new technologies or service requirements. The feasibility of this approach depends on the “adaptability” of products. This characteristic is primarily determined by the design of a product.

This paper discussed “adaptable design”, an emerging design paradigm that includes adaptability among the initial design requirements. AD utilizes any forecast information available to facilitate possible future adaptation. In the absence of such information, there are guidelines that help designers increase the general adaptability of products. These guidelines are based on developing functional modules that interact via flexible interfaces. This is difficult to achieve in mechanical systems due to the rigidity of components and the dependency of functions on forms and dimensions. However, advances in electronics and digital control systems have made it possible to replace many conventional designs with flexible designs. Such technologies are becoming increasingly more affordable, allowing for the development of more adaptable designs in the future. A more detailed discussion on adaptable design can be found in [Gu et al., 2004].

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