

Environmentally-sensitive design: Leonardo WAS right!

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Abstract

The design of environmentally-sensitive products and manufacturing facilities is considered by some members of the industrial community to be one of the current frontiers of engineering practice, while others consider it to be another fad. Here today but gone tomorrow. This paper examines this topic from a biological stance by asserting that humankind's activities should emulate nature's flora and fauna, and the ecosystems that support them. Leonardo da Vinci's profound words of some five centuries ago concerning nature's inventive genius provides the motivation. Subsequently these words are buttressed by a set of fundamental biological canons that provide the basis for engineering design rules governing the efficient management of natural resources. © 1999 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Although human genius through various inventions makes instruments corresponding to the same ends, it will never discover an invention more beautiful, nor more ready nor more economical than does nature, because in her inventions nothing is lacking, and nothing is superfluous.

This sentence was penned some 500 years ago by Leonardo da Vinci, that brilliant painter, draftsman, sculptor, architect, biologist, and engineer in one of his manuscripts [1]. It remains a profound truism at the dusk of the Twentieth Century as some segments of society and indeed some nations are becoming more sensitive to the inability of ecosystems to withstand the incessant abusive behavior of humankind. This sensitivity in the industrial community has spawned the field of design-for-the-environment, sometimes called green design, where the environmental consequences of design decisions is the primary concern. Unfortunately

other members of the community hesitate to embrace this design philosophy. Instead they express concerns about the financial burden of implementing environmentally-sensitive philosophies and the potentially negative response of shareholders to lower profits; or they simply resist the suggested changes because they are considered to be a concept of limited long-term value, unworthy of attention. This debate is the focus of this paper.

The inability of biological systems to withstand continued abuse by humankind is becoming increasingly evident [2–4]. Evidence includes the significant climatic changes, health issues, and various forms of pollution that threaten the survival of many species on the planet. Numerous newspaper articles, papers in professional journals and television documentaries have highlighted the situation and there have been isolated innovative changes in agricultural practices, architecture, and product design to address some of these ecological concerns [2,5–7].

The maturing nexuses between professionals in the biological and engineering communities have been responsible for deeper appreciations of the awesome

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proWess of nature's creations. This realization has, for example, spawned the field of biomimetic materials where naturally-occurring materials provide the genesis for synthetic materials with engineered macrostructures [8,9]. It has also provided a rich source of conceptual designs for products, such as aircraft wings based on ornithological studies, and hook-and-loop fasteners based on studies of the cocklebur seed [7]. However, the impact of this nexus should not be a surprise, nor is it new. Nature-inspired innovations were evident 2500 years ago when the Israelites manufactured bricks for the Egyptian pharaoh using clay reinforced with straw [10]. Thus many design innovations have been inspired by Nature's creative prowess.

Indeed, perhaps Nature's creations should be studied further in an attempt to discover other subtle secrets that could provide new operating procedures for the industrial community. The roles of the engineering design and the materials science communities would naturally be crucial in this new order. After all, they are responsible for the creation of the numerous artifacts — automobiles, product packaging, microprocessor-based systems, and manufacturing plants — enjoyed by the diverse races on the planet. Since these artifacts are woven into the very fabric of civilizations, these two communities have an important role to play in shaping them and their values.

The challenge that confronts the design and materials communities is how to create products and processes, especially manufacturing processes, that impose minimal damage to the environment, while simultaneously enhancing the quality of human life. Herein, the argument for the implementation of environmentally-sensitive design philosophies is based on studies of organisms in diverse ecosystems. The principles they employ appear to provide the basis for sets of rules to be employed in engineering design practice. Indeed, there appears to be little choice if environmental wounds are to be healed and the species is to prosper.

2. Biological rules and their transformation into engineering practice

Table 1 presents a set of canons that is distilled from millennia of natural selection in complicated mature ecosystems [9]. These winning strategies have been adopted by all organisms; hence they have been employed by both animals and plants having diverse organs and parts that harmoniously function together as a whole to sustain life and its activities. Indeed, they provide a set of rules that are worthy of analysis and potential implementation in engineering practice by humankind. After all, homo sapiens is an organism too. The engineering community in particular should con-

sider their embodiment in the creation of new products and throughout the product realization process.

Humankind traditionally adopted the rules presented in Table 1 until the last century or so; but from the British Industrial Revolution onwards, there has been a divergence of thinking between industrial practices and these fundamental laws of nature. Humankind has been guilty of not reflecting on this divergence because man, the toolmaker, is at the pinnacle of the food chain and is able to rapidly respond creatively to dynamically changing environmental conditions. This innovative creative flair coupled with the ability to think logically is in sharp contrast to the instinctive behavior of other species. For example, beavers have always built dams and certain types of birds have always built nests.

Most civilizations typically fail to abide by many of the canons presented in Table 1. Several are broken when humankind generates waste products which are discharged into the environment. This action pollutes the air, water, and soil. Thus three ingredients essential for life are affected adversely. The solution to this problem is complex because of depleted natural resources, third-world poverty, a rapidly increasing world population, and of course, economics.

In the western world, this situation is further exacerbated because pollution is caused by facilities that are desired by society. Factories are responsible for considerable air and water pollution. However, they provide employment and they manufacture products desired by large segments of the population. These products often cause further pollution. This unhealthy situation will only be controlled by a concerted collaborative approach involving scientists, engineers and legislators [11].

The set of canons presented in Table 1 appear to be an appropriate place to start to establish the basis for this concerted collaborative approach. Each canon shall now be briefly discussed before proposing the implications for engineering practice.

2.1. Use waste as a resource

Mature ecosystems are generally self-contained ex-

Table 1
Nature's rules for sustaining ecosystems

-
- Use waste as a resource
 - Diversify and cooperate to fully use the habitat
 - Gather and use energy efficiently
 - Optimize rather than maximize
 - Use material sparingly
 - Don't foul nests
 - Don't draw down resources
 - Remain in balance with the biosphere
 - Run on information
 - Shop locally
-

cept for the influx of water and heat from the sun. They are characterized by growing and decaying organic materials in a never-ending cycle. There is no waste, because the complex inter-play of the different sub-systems ensures that nothing is wasted because decaying materials provide the food for some other organism in the food-chain.

This canon suggests that there should be no household or industrial waste. Everything should be recycled instead of disposing of waste in landfills. Indeed using the ecosystem analogy, industrial enterprises should be situated in complementary groups that interact harmoniously so that the waste from one factory can be easily transported to an adjacent factory where it would be the raw material for that manufacturing facility. This canon also suggests re-manufacturing parts, and design-for-disassembly procedures to facilitate the recycling process.

2.2. *Diversify and cooperate to fully use the habitat*

Mature ecosystems comprise collections of organisms that maintain a balance between cooperation and competition. None-competing niches are formed, backup systems are created, and symbiotic grouping of organisms provides complementary partnerships.

The application of this concept to industrial practice implies that several companies should establish communal resources for the community. Indeed some alliances have already been established to advance the development of materials for specific industrial sectors, appropriate processing technologies, and new technologies, such as fuel cells for automobiles. This has ensured the development of common standards, labeling, and simplification of the recycling process.

2.3. *Gather and use energy efficiently*

Solar energy powers ecosystems directly or indirectly. It is primarily collected by photosynthesizers before being transformed throughout the food chain. This precious resource is consumed carefully, as evidenced by the efficiency of both flora and fauna. Animals minimize the distances to acquire food, enzymes accelerate chemical reactions to create bones and webs, and plants and animals employ many energy-saving devices.

Thus the natural world uses sunlight efficiently to fuel life. Some progress has been made to replicate this process, but humankind primarily consumes the consequences of really ancient sunlight in the form of fossil fuels. Therefore lightweight materials should be developed for energy consuming applications, such as linkage machinery or transportation systems, and heat should be consumed efficiently during manufacturing processes because the intense pressures, high temperatures, and consumption of such large amounts of en-

ergy would not be tolerated in a natural system where creation occurs at ambient conditions. On the societal level, both manufacturing facilities and the local production of electrical energy could be distributed nationwide rather than employing the current practice of central facilities with a global network that incurs distribution losses.

2.4. *Optimize rather than maximize*

Mature ecosystems require the creation of optimal solutions to problems rather than maxima or minima because of their inherent complex inter-relationships. The need for diversity and cooperation in an ecosystem mandates these less aggressive approaches too. Mathematically, this is ensured because with this class of optimization problems, a complex set of constraints are imposed on the objective function in the search domain.

In today's mass production environment, speed and high production volumes are critical. This search for maxima contrasts with the slow rate of production in a biological system. The rate of change in some fields of engineering is rapid and assures obsolescence and a large waste stream to the landfills. In others, this is not true. If modular designs could be employed to extend the service life of products, along with greater emphasis on maintenance, recycling and re-manufacturing, then this approach could yield solutions rather closer to optima instead of maxima.

2.5. *Use material sparingly*

Natural artifacts are created with only enough material to perform their intended function. Furthermore, these durable innovative artifacts are typically multifunctional, serving several purposes. Consider the low drag profile of the porpoise which also houses all of the body organs, or the lightweight structure of a bone and its roles in skeletal and mineral homeostasis.

The manufacture of products with less material implies a reduction of pollution, less energy is consumed by manufacturing facilities, and there is less material entering the waste stream or recycling facilities. Superior alternatives can sometimes be achieved by employing lightweight structural design methodologies, or by selecting alternative materials.

2.6. *Don't foul nests*

Organisms generally reside and manufacture in the same location. They don't pollute in this region because it would directly impact adversely on their quality of life; namely, food supply, sleeping and breathing. An optimal solution to the quest for energy conservation and the consumption of materials has been achieved.

Thus humankind should reduce industrial and domestic pollution to levels that can be assimilated by planet Earth. Naturally, pollution has many forms, so the ramifications for the engineering community are immense. They include the re-design of products, manufacturing processes and equipment, recycling, and the development of other waste recovery schemes.

2.7. *Don't draw down resources*

Parasites don't kill their hosts and predators don't kill all their potential prey. As food becomes scarce, more energy must be expended to acquire it. Under these conditions a natural genetic feedback loop triggers an alternative strategy. Thus, different sources are sought so that replenishment is permitted.

Clearly, humankind should not consume renewable resources faster than they can be replenished. Secondly non-renewable resources should not be consumed faster than substitutes can be created. In particular, the dependence on fossil fuels during the past 200 years or so must be examined and alternative sources created, such as fuel from corn and plastics from plants.

2.8. *Remain in balance with the biosphere*

The land, air and water that sustain life is in a state of equilibrium. This equilibrium is sustained at many different levels, it is a complex multi-loop activity and it involves numerous chemical compounds with recycling.

Humankind has generated an imbalance in atmospheric carbon dioxide through the burning of fossil fuels and deforestation. These global consequences of our abuse of the biosphere, coupled with dramatic climatic changes, mandate a re-evaluation of how sustainable, stable lifestyles can be assured.

2.9. *Run on information*

Complex ecosystems feature sensors, actuators and intelligent processors with sophisticated control algorithms that are interconnected with information transmission systems involving feedback loops. Everything interacts harmoniously and maintains homeostasis. Currently humankind abuses the planet by consuming more than can be naturally replaced and generating more waste than can be assimilated. Companies need to be inter-connected to help coordinate the consumption of waste while monitoring the environment. Governments could conceivably be involved too; rewarding good practices with taxation incentives, while imposing higher taxes on companies not complying with environmental laws.

2.10. *Shop locally*

Organisms acquire and consume local food as part of

a food-chain. This complex biological system is in sharp contrast to humankind's, where food and raw materials are often transported considerable distances. This is accomplished by a transportation industry that consumes considerable energy while polluting the environment, and a packaging industry that generally uses a large amount of plastic that is discarded into the waste stream following a brief service life.

3. Design for the environment

Commercial facilities, industrial plants and the products that they manufacture are responsible for how materials and natural resources are used. To be environmentally more sensitive, the fundamental canons of Table 1 must be infused throughout these organizations in order to reduce the environmental burden of industrial processes and the products they manufacture. This assertion pertains to the complete product realization process. Hence it pertains to the extraction of raw materials from which the product is to be made; the processes to be employed to manufacture the product; the distribution of the product to the customer; the life of the product; and also its disposal. The impact on the environment of industrial facilities and all classes of products is a direct consequence of design decisions. Decisions made at the conceptual design stage are responsible for over 70% of the costs of product development, manufacture and service [7]. Fig. 1 and Table 2 present the kernel of the design-for-the-environment philosophy for industrial practice based on the transformation of the biological canons in Table 1.

While this paper contains several tables documenting some basic rules for environmentally-sensitive design, one of the current challenges of this embryonic engineering discipline is how to determine whether one product is 'greener' than another? How should several solution candidates be evaluated? How should compromises be made? Namely, how should the design

Table 2
Principles of green design

-
- Use all materials optimally
 - Select materials that minimize pollution during extraction, processing, deployment, recycling and disposal
 - Use all energy resources optimally
 - Ensure that the product has minimal adverse affects on the environment during manufacture, deployment and disposal
 - Evaluate product disposal methods
 - Ensure that the product service life is appropriate
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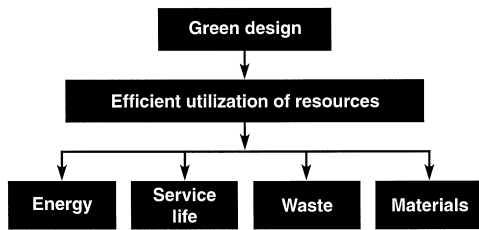


Fig. 1. The primary attributes of design-for-the-environment.

community determine whether one complex multi-part product is environmentally superior to another?

As an illustrative example, consider the common electric light bulb. The conventional incandescent light bulb is a highly inefficient light source that generates light from only 5% of the energy it consumes. The remaining 95% is wasted as heat. This is highly inefficient and is a poor product from an environmental perspective. Fluorescent bulbs consume 75% less energy to generate the same amount of light. Their energy efficiency makes them a much 'greener' product. However, fluorescent bulbs contain mercury that can damage the human nervous system. Thus in the context of heavy metal pollution, they are not as green as the conventional bulb!

4. Management of natural resources

Design-for-the-environment is concerned with the management of natural resources. Herein this topic shall be considered in the context of the management of materials and energy.

4.1. Materials management

Materials management is an important cornerstone of environmental design, but it is a difficult undertaking [12]. The material selection process is exacerbated by the observation that several thousand chemicals are manufactured in industrial quantities and new ones are being developed continually.

Two basic extrema rules are offered subject to diverse constraints, including economics, that may permit an optimal solution to be obtained rather than a true extrema: minimize waste generation during the extraction of raw materials and also during the life-cycle of the product; and maximize recovery, recycling and re-manufacturing throughout the product's service life. From an environmental perspective these issues are just as important as the inherent properties of the material. Fig. 2 presents a network diagram of this philosophy and Table 3 presents some principles derived from the fundamental canons presented in Table 1.

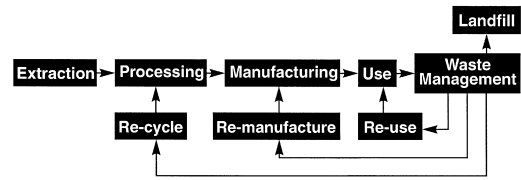


Fig. 2. Materials management.

4.2. Minimize material utilization

The logical first goal of materials management is to reduce the volume of material in a product. By implementing this approach there is a reduction in the consumption of raw materials, a reduction in pollution associated with extraction and refinement of the material, a reduction in the pollution and energy consumption during the subsequent manufacturing phase, and a reduction in the volume of material entering landfills. Thus it complies with several of the canons from Table 1. The implementation of this principle has been responsible for reducing the weight of beverage cans by 30%, grocery bags by 70% and plastic milk bottles by 40% during the past 20 years in the USA.

4.3. Recycling materials

The second goal of materials management is to use recycled materials or re-manufactured parts rather than virgin materials whenever possible [3,13,14]. Again, this design rule complies with several of the fundamental canons in Table 1. The specification of recycled materials reduces the volume of the waste stream entering landfills, it reduces the consumption of natural resources that may need to be transported large distances, and it permits higher efficiencies to be achieved by the processes employed to manufacture products.

Some of the design issues to be addressed before

Table 3
Principles of materials management

- Minimize the amount of material in each part
- Lengthen the service life
- Specify re-cycled materials whenever possible
- Specify energy-efficient materials in manufacture and in service
- Specify materials that pollute minimally during their extraction, manufacture, use, and disposal
- Specify readily available materials that do not deplete declining natural resources
- Specify materials that are unlikely to be affected by new legislation that will constrain their deployment, manufacture, or disposal

Table 4
Principles for materials recycling

-
- Minimize the number of different materials in a product
 - Select easily recycled materials
 - Ensure easy of product disassembly
 - Facilitate material identification
-

materials can be economically recycled are itemized in Table 4. While waste disposal costs have continued to increase steadily during the past few years, this must be considered in the context of the economics of recovery. The important parameters include collection costs, sorting costs, and re-processing costs relative to the cost of acquiring virgin materials.

For example, recycling aluminum waste reduces the energy consumption by 95% relative to the processing of bauxite, and the recycling of glass can reduce energy consumption of glass products by 75%. One-third of the US steel production is currently undertaken by minimills using scrap iron. The implementation of this philosophy is responsible for the following environmentally-desirable reductions: 97% in mining waste; 90% in consumption of virgin materials; 86% in air pollution; 76% in water pollution; 74% in energy consumption; and 40% in water consumption. This desirable recycling of materials is becoming more widespread in the USA and the percentages of annual metal consumption derived by recycling are, as follows: lead 55%; steel 50%; copper 43%; aluminum 32%; and zinc 19%.

In order to recycle a material, it must first be identified and it must be separated from other materials. Table 5 presents some design rules for addressing these issues [11].

Material recycling is facilitated when products contain the smallest number of different materials. Of course compliance with this principle is dependent on the type of product and upon the maturity of the recycling processes for the materials used to make it. The recycling of any material is enhanced when parts can be easily separated through the implementation of design-for-disassembly rules. However, once parts have been separated in a recycling facility the next task is to identify the materials from which the parts have been fabricated. This is no easy task because there are

Table 5
Principles of design-for-disassembly

-
- Minimize the variety of materials in a product
 - Consolidate parts
 - Reduce the number of assembly operations
 - Specify compatible materials
 - Simplify and standardize the fits
 - Identify separation points between parts
 - Specify water-soluble adhesives
 - Incorporate a material identification scheme on parts to simplify identification
-

thousands of materials in the marketplace: thermosets, thermoplastics, and the commercial metals for example.

Whenever possible, high quality materials should not be degraded with contaminants during re-manufacturing or recycling. For example, a small percentage of copper can reduce significantly the value of scrap steel. Contaminants are often difficult to remove from primary materials and the desirable properties of these primary materials can be progressively degraded during repeated recycling. Consider for example the recycling of the plastic polyethylene terephthalate (PET) which represents 30% of the plastic bottle market. Commercial separation can be a difficult undertaking because of contamination by several polymeric contaminants with the same specific gravity as PET. If the primary material is degraded by repeated recycling then it might be appropriate to recycle the material into products requiring a lower quality material, before finally incinerating the plastic to retrieve some of its intrinsic energy.

Another challenge of recycling is the economic retrieval of expensive materials from parts. Consider the identification of parts fabricated from expensive materials, such as platinum in automobile catalytic converters and cadmium coating on bolts. How are these rare materials to be economically retrieved?

Plastics are relatively inexpensive to process and they are extremely versatile. Thermosets can be granulated and mixed as a filler material for new thermoplastic products, and thermoplastics can be recycled. However, they do pose ultimately a significant waste disposal problem because they do not readily decompose and they currently constitute over 20% by volume of solid municipal waste in the USA.

At the end of their service life, most multi-part products comprise a collection of parts performing at various levels relative to their respective design specifications. Some parts are worn and need replacing; some are technologically dated; and some are still state-of-the art and still perform in compliance with their design specifications. This latter group includes structural members manufactured by sand casting or welding, and off-the-shelf items, such as bolts and plastic tubing. Such parts can be incorporated within a new product with minimal re-working. Other parts, such as multi-element anti-friction bearings might be worn and need replacing. While other parts might need to be re-manufactured. Hence, new parts would be introduced and others refurbished. Products that are most easily re-manufactured are those with a small number of design changes each year. The implementation of this philosophy encourages the extension of the service life of the product through a waste prevention approach manifested by the re-cycling of materials and parts.

Diverse sets of parts families and products can be re-manufactured, ranging from aircraft to rifles; automotive parts like clutches, carburetors and starter motors; and parts for photocopier machines. This re-manufacturing philosophy encourages the development of modular designs, where a dated module can be replaced by a state-of-the-art module; standardization, that permits one part to be used in several different products; and the implementation of design-for-disassembly principles, which facilitate the dissection and separation of products into individual parts.

4.4. Extend the service life

The third goal of materials management is to lengthen the service life of the product. The motivation for this approach is to ensure that fewer products enter landfills, or reprocessing facilities, each year. Products have been typically discarded into the waste stream once their performance no longer satisfies the design specification, or the perceived needs of the customer. This situation can be affected by the emergence of new styles, new technological features and new maintenance protocols. Table 6 presents a list of principles for extending the service life of products.

Products should be designed by employing design-for-maintenance principles so that worn parts can be easily replaced. Documentation should be user-friendly and maintenance manuals written carefully. Maintenance procedures should be simplified so that the customer can complete these tasks whenever possible rather than return the product to the manufacturer for service or to a special service center. Sensors and microprocessors, already present in many classes of products, provide the basis for enhanced fault identification and guidance with repair procedures.

A compromise must frequently be established between the advantages of extending the service life of products and the effect on the environment of the consumption of additional materials and energy to do

Table 6
Principles for extending the service life of a product

-
- Create user-friendly documentation for repair and maintenance
 - Ensure that the life-cycle is environmentally optimal
 - Replace worn parts
 - Replace parts with a new generation of parts
 - Identify the inherent weaknesses in a product and re-design to avoid premature failure
 - Identify potential hazards associated with the product at the end of it's service life and minimize them
 - Use design-for-disassembly principles to facilitate the re-manufacture and re-cycling of parts
-

this. For example, a compromise might be needed between the selection of a material which ensures that a part has a long energy-efficient service life, and the environmental consequences of extracting, processing and manufacturing the part from that material. Economics, legislation and the environmental values of the populous concerning single-use disposable products are some of the primary ingredients of this class of environmental dilemmas.

Many products contain a combination of traditional technologies, such as weldments or castings, and new technologies, such as microprocessors and sensing systems. While the changes in the former class of technologies is slow, the latter class can evolve quickly. Under these conditions, can product upgrades be facilitated by creating modular designs where an old module is rapidly replaced by a module comprising of new technologies to prevent the product from entering the waste stream? The photocopier industry has aggressively embraced green design [15]. Agfa-Gevaert, for example, extended the average life of one of their photocopiers to 8 years by implementing this philosophy when the industry average was only 4 years.

4.5. Energy utilization

Energy conversion is the primary cause of pollution and global warming. It is imperative, therefore, that designers strive to create energy-efficient products and seek environmentally-friendly sources of power. Obviously products that consume energy must be designed to minimize the consumption of energy and use it efficiently as stated in Table 1. A set of principles for energy utilization is presented in Table 7.

The power consumption of a product must be considered at the conceptual design stage by incorporating large weighting factors in evaluative matrices used to select appropriate concepts for further development [7]. These considerations ultimately translate into considerations of alternative materials, parts, insulation, sub-assemblies, tribology, and heat recovery systems at the product design phase. Sensors, actuators and microprocessor-based control schemes also merit consideration in the creation of energy-efficient designs.

The selection of an appropriate environmentally-sensitive energy source for a product is a challenging task. It involves both the efficiency of the final product and also the efficiency of the method used to generate the chosen source of energy. While the former problem

Table 7
Principles for energy utilization

-
- Minimize energy consumption
 - Minimize energy losses
 - Choose sustainable fuel sources
-

involves both conceptual and product design attributes, the latter might be beyond the control of the local design community.

Consider a popular source; electrical energy. This is generated by a wide variety of different approaches that differ significantly in their environmental friendliness. Coal-fired, gas-fired or oil-fired power generating stations consume non-renewable fossil fuels, and they are frequently inefficient and pollute the atmosphere. Nuclear stations also have environmental problems. However, electricity can be generated using renewable resources, such as wind, tidal, ocean-wave, solar, hydro-electric or geothermal sources.

Green design methodologies concerning energy utilization have been applied to a diverse range of products with some success [6,16]. For example, the domestic refrigerator has been the subject of many studies because it typically uses one-fifth of the energy consumed by the average household in the USA. Current efforts to enhance the performance are focused on developing better insulation and door seals, and more efficient evaporators, condensers, motors and compressors.

A review of domestic washing machines and dishwashers reveals that some products consume twice as much energy as others. New generations of machines can consume 50% less water and 50% less detergent. Furthermore they operate with lower water temperatures, they consume less energy and the fabric of the clothes is damaged less. There are also new generations of energy-efficient clothes dryers that employ sensors and microprocessors to monitor the dryness of clothes instead of using a clock and an open-loop algorithm to control the drying process. Thus when a prescribed dryness is attained, the appliance automatically switches off instead of wasting heat on clothes that are already dry.

The transportation industry, a non-trivial segment of the economy, has been increasingly focused on energy efficiency. Automobiles have been the subject of the most severe legislation to reduce harmful exhaust emissions and enhance fuel consumption in the USA because this product is responsible for significantly contributing to atmospheric pollution and global warming. Much effort has been expended to reduce aerodynamic drag and vehicle weight, while developing alternative fueled vehicles and more efficient engines with sensors and microprocessors.

5. Conclusions

Five-hundred years ago Leonardo da Vinci recorded an observation of the limitations of human creativity relative to the creations of the natural world. This observation remains a profound truism despite the advent of the scientific method, the infinitesimal calculus and powerful digital computers. Humankind has failed to comply with this truism and we are now confronted by several major challenges because of our failure to abide by this edict. A study of organisms in diverse ecosystems permits a set of general canons to be established that are worthy of adoption. By developing design rules based on these fundamental canons, more environmentally-sound manufacturing facilities and products can be created. The implementation of these design rules in practice should have profound consequences for planet Earth and our quality of life.

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