1

Performability Engineering: An Essential Concept in the 21st Century

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Abstract: The concept of performability is explained and the desirability of using this attribute in pursuing the design of engineering products, systems, and services is emphasized in order to meet the challenges of the 21st century. Today a new revolution is taking place where the leaders will be those nations that provide priority to the principles of sustainability in order to design, develop and use products, systems and services that are not only dependable but do not lead to disrupt the delicate ecological balance in nature. New materials, technologies and processes in consonance with environmental protection hold the key to future progress and prosperity.

1.1 Introduction

Over thousands of years, man has constantly innovated and contrived to exploit Earth's natural resources to improve his quality of life, well-being and prosperity. Whereas the last industrial revolution helped improve the living standard of man, it also caused immense damage to the environmental health of the Earth. Today another revolution is in the offing and the world is witnessing an unprecedented development in all scientific and technological fields. This can be attributed primarily to phenomenal advances made in the area of computer hardware and software, communications and information technology. It goes without saying that new areas like genetic engineering, biotechnology, nanotechnology hold the key to the development of sustainable products, systems and services in future. In fact all future technological pathways would aim to prevent and minimize, if not reverse the damage that was already done to the Earth's environment during the last industrial revolution.

1.1.1 The Fast Increasing Population

The rapid increase in the human population is a matter of concern for the people living on this planet since in the entire solar system Earth alone has a habitable atmosphere for sustaining life, which actually evolved thorough a series of delicate balances of several factors over billions of years; it took some 3.5 billion years before human life emerged from simple living cells, which themselves emerged through a unique sequence of combinations of molecules after the Earth was formed.

Since the appearance of *Homo Sapiens* on Earth, until 1900 the world population could only grow to a level of 1.6 billion people. However, by 1930, it had risen to two billion and by 1960 it had reached three billion. By 1975 it had risen to a level of four billion, and by 1986 it was five billion; in 1999 it had already crossed the level of 6 billion. In fact, now we are adding more than 200,000 people every day. Today, we are about 6.5 billion people on Earth. Thus there has been an exponential growth in the last century as compared to the earlier centuries. The United Nations medium population projections show that the world population will reach the level of 8.9 billion by 2030 and is likely to level off at 14.5 billion by 2150. Also, even according to the U.N. Long-Range World Population Projections, the world population, under the most favorable conditions, is likely to reach a stable level of 11.5 billion by 2150. In any case, the increase in population even on the basis of most conservative estimates is likely to put tremendous pressure on the Earth's resources and will threaten the ecological balance that exists on Earth. Needless to say, every inhabitant of this planet needs to share the available resources on this planet and the Earth is the last habitat of humanity in the entire solar system as we have nowhere else to go.

Many planners think that populating other planets may be a solution to ease the population pressure on Earth. However, the technology to transport even a limited proportion of the population to any nearby planet where conditions may be favorable for humanity to survive, is non-existent and by the best technological forecasts, it cannot be developed at least for next 100–150 years. In fact by that time, we would have already done irreversible and irreparable damage to our planet.

Therefore, we have to find ways and means to sustain the human population on Earth without further damaging its environment and must even try to regenerate, if possible, its environmental health. It must dawn on all human beings living on this planet that we are living on an island in space, called Earth and that we cannot possibly escape living on it. The only recourse left is that we must mend our ways if we, and our future generations, regardless of their geographical location or nationalities, are to survive and flourish on this planet. Our problems are the problems of the planet Earth.

As the human population grows, there will be less for everyone in terms of food, clothing, materials and energy. People in the USA, who enjoy the benefits of a rich life style, might have to reconcile to being satisfied with less. Ideally, everyone on this Earth would like to maintain a wonderful lifestyle. With resources shrinking, the cost of raw materials is likely to escalate in a spiral fashion in future and the *per capita* share of world resources will also decrease. We have already witnessed this phenomenon in the case of oil prices, which have been steadily increasing over the past few decades and have more than doubled in the past few years. Likewise, other exhaustible resources are also likely to cost more in the near future.

1.1.2 Limited World Resources

The fast population growth of human beings has resulted in a fast depletion of resources on Earth. For resources of the Earth, whether they are renewable or non-renewable, if adequate care is not taken to control the rate of their use, there will always be a risk of degradation of the environment. Renewable resources can maintain themselves or can continuously be replenished, if managed properly and wisely. Food, crops animals, wildlife, forests along with solids, water and air belong to this category. We must not forget that the resources on Earth were not only meant for human beings alone but were also meant to sustain the rest of the living creatures on this planet. For this category of resources, the point of concern is not that we may run out of their supplies but that we may use them faster than they can be regenerated and if humans do not restrict to their equitable share of resources, other living beings or species on Earth will be endangered.

On the other hand, non-renewable resources like coal, oil, iron, aluminum, copper, tin, zinc, phosphates, *etc*., are exhaustible and can become depleted and their exploitation beyond sustainable levels may create severe adverse environmental effects threatening to cause irreparable damage to fragile eco-systems through which life on Earth is sustained.

There are several compulsions for using Earth's resources wisely, more efficiently, distributing them more equitably, reducing wastage and in fact reducing their overall consumption levels. The gap between developed nations and developing nations is widening. While writing these paragraphs, I have a newspaper item before me stating that Britons waste one third of all the food they buy (which is estimated at about 3 million tonnes), thereby wasting the money and energy used in producing it. On the other hand, there are undernourished people in Africa and Asia. Any kind of wastage either of materials, energy or food must be curbed. This is not only necessary for our survival and existence but also to have sustainable development so that human beings and their future generations can live and prosper without tension or wars over sharing the limited resources on this planet.

In any case, we have entered an era in which global prosperity will depend increasingly on using the Earth's resources wisely and more efficiently, distributing them more equitably, reducing wastage and in fact reducing their overall consumption levels. Unless we can accelerate this process, serious social tension is likely to arise, leading to wars and destruction of resources. The Gulf War is an example resulting from increased competition for the right of sharing scarce resources like oil. Eventually, the world might even be heading for an unforeseen catastrophe. The next scarce resource on the list may be water and sharing it may lead nations to strife.

1.1.3 The Carrying Capacity of Earth

The *carrying capacity* is defined as "The number of individuals of a given species that can be sustained indefinitely in a given space". This in the context of the number of human beings being sustained indefinitely on the planet Earth is called the *carrying capacity of Earth*. In other words, a population below the carrying capacity of the Earth can survive forever. We know that the Earth today has about 6.5 billion people. What we may want to know is how many people can survive on the Earth without damaging the Earth as the habitat of human beings. If we crowd the Earth too much, then it may affect the Earth's ability to support human beings indefinitely. Life will get worse and after a while, humans might start decreasing in number, or may even become extinct, as is happening with several other species.

On the other hand, if we find the right number of people and the right type of resources and energy to meet their requirements, then we will be able to support many people on Earth for a very long time – the humanity will be able to survive for thousands of years without compromising the standards of living. Of course, there are several controversial estimates for the carrying capacity of Earth. Some scientists put it at 40 billion and some put it merely at 2 billion – a level that we have already crossed, but what is certain is that if we do not bother about it, sooner or later we will have to face that impending disaster. If we conserve the Earth's resources, clean up pollution, and apply our present knowledge and technological advancement to finding less damaging ways of satisfying our needs, the carrying capacity can be improved. For instance, if we prevent pollution of water (also air and land) and clean up water that is already polluted, then we will be able to grow more food and more people can be supported. We know that the last industrial revolution improved the standard of living for some but damaged the pristine environment of several industrialized nations. All this happened since nobody bothered about pollution of free resources (we do not pay for preserving them) like air and water. Sustainable development would not allow that to happen again.

1.1.4 Environmental Consequences

On the other hand, the unprecedented technological developments during the last century have dealt a severe blow to the environmental health of the Earth; man's insatiable quest for a better quality of life coupled with economic disparities between people [1] has further changed the consumption pattern drastically and the choice of technologies. There has been more over-exploitation causing serious environmental consequences and wastage of resources during the past two decades than any time during the history of mankind. The depletion of ozone layer, CO_2 concentrations and pollution of rivers and water bodies including ground water makes drinking water a valuable commodity. The winter of 2007 has been the warmest since 1880. Glaciers are receding and snow is melting. There are severe floods, forest fires and landslides in places least thought of earlier. These consequences flow from environmental degradation. In fact this phenomenon has led man to surpass the carrying capacity of Earth. The Brundland report [2] was an eye opener for all of us. In fact, realizing the gravity of the situation as early as 1992, more than 1600 scientists, including 102 Noble laureates collectively signed a Warning to Humanity, which reads as follows:

"No more than one or a few decades remain before the chance to avert the threats we confront, will be lost and the prospects for humanity immeasurably diminished… A new ethics is required – a new attitude towards discharging responsibility for caring for ourselves and for Earth… this ethics must motivate a great movement, convincing reluctant leaders, reluctant governments and reluctant people themselves to affect the needed changes".

However, due to the lack of political will and a clear understanding of the consequences of our inaction, not much has been done in the direction of taking some firm steps towards the implementation of resolutions made at several world meetings attended by world leaders. Developed countries and developing countries instead keep blaming each other for the present malaise and never come an agreement and precious time for humanity is being lost for ever.

1.2 Technology Can Help

Naturally, to keep pace with rising population, the increased volume of production to meet the demand is likely to affect the world environmental health further unless technology is put to use and pollution prevention measures are vigorously pursued. Therefore, the importance of the control of effluents and waste management along with minimization of energy and material requirements (dematerialization) requirements can hardly be emphasized while ensuring an acceptable level of performance of systems, products and services.

Technology can certainly help increase the carrying capacity in several ways, if we are able to improve upon the technology and use it wisely. For instance:

- Since we have a limited reserve of gasoline on the planet Earth, we need to build cars that will give better mileage. If each car uses less fuel, then we can serve more people with the same amount of gasoline.
- Also using newer catalytic converters, we can make vehicular emission, which contributes 25% of the world's total CO_2, which is the single major factor leading to global warming, completely free of gases causing air pollution and carbon loads.
- If we were to increase the number of telephones by using old-fashioned standard phones, we would need many, many kilometers of wire to connect all those phones and the copper for the wires will have to be mined and the process of mining uses a huge amount of fuel energy and would cause a considerable amount of pollution of land, water and air. On the other hand, if we use wireless cell phones, we do not need wires, and we can save all that fuel and pollution. Fortunately, this revolution has already taken place.
- If we use new genetically engineered plants that can be grown in dry climates and are resistant to disease, or with increased nutrition, we can grow the plants on new farms, without the use of pesticides, and produce a better crop. Of course, we will have to ensure that this happens without any risk to humans and that these new plants in themselves do not harm our environment.
- In fact, new sustainable technologies have the promise of reducing energy requirements of products and systems considerably. This has happened in the case of microminiaturization of electronic devices. A laptop today consumes negligibly less power than a computer of 1960, which used tubes and was highly inefficient and unreliable. After all Moore's law applies to electronic hardware development. Why will

this not happen if move over to the use of nano-devices?

Therefore, it is quite understandable that several possibilities exist for using technology to our advantage to prevent pollution and wastage of resources to help increase the carrying capacity of Earth.

1.3 Sustainability Principles

It is true that no development activity for the benefit of human beings can possibly be carried out without incurring a certain amount of risk. This risk may be in terms of environmental degradation in terms of pollution of land, water, air, depletion of resources, cost of replenishment or restoration to acceptable levels both during normal operating conditions and under the conditions of sudden hazardous releases on account of catastrophic failures or accidents. In the past, we have witnessed several technological (man-made) disasters, which had their origin in our underscoring the importance of ensuring the best level of system performance and its linkages to environmental risk.

There is a severe requirement of material conservation, waste minimization and energy efficient systems. Recycling and reuse must be given serious consideration if nonrenewable resource consumption is to be minimized or energy use associated with material extraction is to be conserved. Use of renewable energy sources has to become the order of the day. The same is true about the prevention of pollution of *free resources* like water and air, which are also required for sustaining life support system of the planet we live up on.

One of the important strategies of implementing sustainability is to prevent pollution (*rather than controlling* it) and this by itself cannot be viewed in isolation with the system performance. A better system performance would necessarily imply less environmental pollution on account of system longevity and optimum utilization of material and energy for limited resources scenario that governs the development of future systems. It is also naturally an economic proposition. In other words, sustainability depends very heavily on the performance characteristic of a system. Therefore, the objective of a system designer should be to incorporate the strategy of sustainability in all future system performance improvement programs and designs.

The key issues associated with the implementation of the sustainability characteristics of a system appear to revolve around:

- The need to conserve essential natural resources, minimize the use of materials, develop renewal energy sources and avoid overexploitation of vulnerable resource reserves.
- The need to minimize the use of processes and products that degrade or may degrade the environmental quality.
- The need to reduce the volume of waste produced by economic activities entering the environment. The quantum of waste is colossal. For example, every three months, enough aluminum is discarded in North America to rebuild the entire North American commercial airline fleet.
- The need to conserve and minimize the use of energy. For example, if recycled the energy requirement for aluminum is just 5% of the energy used in original production.
- The need to reduce or prevent activities that endanger the critical ecological processes on which life on this planet depends.

1.4 Sustainable Products and Systems

The sustainability principle requires that the products and systems use minimum material (dematerialization), and minimize the use of energy throughout their entire life cycle (extraction phase, manufacturing phase, use phase) and they should use non-hazardous materials and should be highly recyclable at the end of their life. Minimizing the use of matter minimizes the impact of the extraction phase and minimizes total material flows. Historically, the United States environmental activities have been driven by regulation. They were focused more on the factory, on emissions from the factory. Consequently, R&D in the United States has focused very much on activities like the factory-eliminating CFCs, reducing the emissions of volatile organic compounds (VOCs), improving water quality and such types of issues. Whereas in Europe, environmental policies are being increasingly pursued to address the overall environmental impacts of a product over its entire life cycle right from raw materials extraction, product manufacturing, product use, and disposal or recycling.

The European Union's Integrated Product Policy (IPP), which seeks to stimulate demand for greener products and to promote greener design and production (Commission of the European Communities, 2001) is a step in that direction. European Union's WEEE directives also can be considered as a step in that direction. In Japan, much emphasis is being put on the environmental design of products and systems, driven both by the concern over scarce resources and as a business strategy. The emphasis is on extensive recycling of products and environmental attributes such as energy efficiency and the use of non-toxic materials. In Europe and Japan, increasing attention is being paid to materials flow analysis as a means of assessing resource efficacy and sustainability. Materials flow analysis, the calculation of flows of materials from cradle to grave, is being used to complement risk analysis and to provide insight into the challenges of sustainable use of resources. These developments indicate an international shift in emphasis from managing individual manufacturing wastes and emissions to managing the overall environmental impacts of industrial sectors and of products over their life cycles. In response, global industrial firms in the United States, Europe, and Japan, are beginning to apply these concepts to their products, manufacturing processes, and environmental programs. Since the 1970s, there is growing evidence to suggest that greater material efficiency, the use of better materials, and the growth of the service economy are contributing to the *dematerialization* of the economy.

The economic growth in developed countries is no longer accompanied by an increased consumption of basic materials. This dematerialization has been investigated for a range of materials including steel, plastics, paper, cement, and a number of metals. Also, as the sources of energy have shifted from wood and coal to petroleum, nuclear energy, and natural gas, the average amount of carbon per unit energy produced has declined, resulting in a *decarbonization* of world energy. These strategies will influence the way product and system designs are designed and manufactured in future.

In fact products, systems and services will be evaluated based on a life-cycle assessment of a product. A life-cycle assessment (LCA) evaluates the entire environmental impact of a product through its life cycle, including manufacturing, use and disposal. A great deal of work has been done to develop the technical foundations for LCA of products and processes, and to develop the databases necessary to support such assessments. The International Organization for Standardization (ISO) is working on formalizing LCA methods. Future products and systems would have to confirm to tenets of DfE (Design for Environment) methodologies.

The phenomenal advances made in information technology have built up great hopes in other technological pathways for sustainable development. Today, newer and smart materials that include composites, high strength plastics and biodegradable materials combined with material recycling and minimum effluent and waste-producing processes, the use of clean energy sources and ever-decreasing levels of energy requirement are some of the strategies that will govern the design and use of all future products, systems and services in the 21st century. New, renewable energy sources are likely to influence the design of future products and systems. It is expected that clean fusion technology will replace the present dirty fission technology in future, provided that the same is proved to be dependable, safe and sustainable.

As stated before, genetic engineering, biotechnology, nanotechnology and molecular manufacturing may provide immense possibilities to developing sustainable products, systems and services that may create minimum adverse effects on environment and last long while using minimum material and energy requirements. All this would require new technological pathways to minimize if not reverse the damage that has already been done to the Earth's environment, if humanity is to survive on this planet.

Certainly, these factors cannot be considered in isolation of each other. Therefore, it is time to take a holistic view of the entire life cycle of activities of a product or system along with the associated cost of environmental preservation at each stage, while maximizing the product/system performance.

1.5 Economic and Performance Aspects

Classical economic theories that have treated nature as a bottomless well of resources and infinite sink for waste have to be discarded. Environmental costs, *i.e.*, the cost of preventing or controlling pollution and ecological disruption, must be internalized. In fact, it is our incapability to deal with the economic nature of environmental pollution that has been largely responsible in destroying the Earths' ecological systems. Many hidden environmental costs incurred on resource exploitation need to be passed on to the consumer or user.

To preserve our environment for future generations, the internalization of hidden costs of environment preservation will have to be accounted for, sooner or later, in order to be able to produce sustainable products in the long run. It is therefore logical to add these hidden costs to the cost of acquisitioning a product or a system.

Also, technological innovations are not without cost to the society. In fact, today leadership among the industrialized nations is judged by the amount of money a country spends on the R and D and by the number of personnel it employs for this effort. In the past, Japan was known as a nation that has turned technologies and know-how into the world's highest quality products. Now, the Chinese have excelled in the skill of making products that are known for being cheaper in cost and better in quality than their counterparts elsewhere in the world. They have invested very heavily in the development of industrial infrastructure over a period.

A recent survey shows that consumers are willing to pay up to 10% more to have an environmentally preferred product. But what does an environmentally preferred product mean, what characteristics of a product will a consumer pay more money for? It is known that consumers in Europe are more willing to pay a premium than consumers in the United States, but the definition of what attributes are important is still just at the beginning.

As of now, the performance of a product, system or a service is usually judged in terms of dependability, which can be called an aggregate of one or more of the attributes of survivability, like quality, reliability, maintainability, *etc*., and safety, of course, not overlooking the cost of physically realizing these attributes. These attributes are very much influenced by the design, raw material, fabrication, techniques and manufacturing processes and their control and, finally, by the usage. These attributes are interrelated and reflect the level or grade of the product so designed and utilized, which is expressed through dependability. In fact, as of now, dependability and cost effectiveness are primarily seen as instruments for conducting the international trade in the free market regime and thereby deciding the economic prosperity of a nation. Therefore, we can no longer rely solely on the criteria of dependability for optimizing the performance of a product, system or service. We need to introduce and define a new performance criterion that would take the sustainability aspect of developing a product or system into consideration in order to take a holistic view of the performance enhancement along with the remedial or preventive costs associated with environmental pollution.

The ever-increasing complexity of systems has further necessitated reliability of components and subsystems, the safety of human beings and the protection of our environment. Especially high-risk systems such as nuclear power plants and other chemical plants have warranted operational safety of the highest order. Besides economically endangering environmental safety or human life, costly projects such space probes can be economically disastrous when such a system fails. Even on the basis of economic considerations, a designer is left with no option but to look for high reliability of systems as the cost of down time results in a crushing sum. For example, the power replacement cost when a moderate-sized nuclear plant is shut down may run over U.S. $80,000. The loss of several billion dollars besides the loss of human lives was involved in the total failure of the Challenger mission.

Another economic consideration that is important for developing future products and systems is to utilize obsolete products at the end of their life for recycling or reuse. If obsolete materials are not recycled, raw materials have to be processed afresh to make new products. This represents a colossal loss of resources as the energy, transport and environmental damage caused by these processes is large. In 1998, it was estimated that six million tonnes of electrical equipment waste causing a loss of resources in Europe was:

- 2.4 million tonnes of ferrous metal
- 1.2 million tonnes of plastic
- 652,000 tonnes of copper
- 336,000 tonnes of aluminum
- 336,000 tonnes of glass

besides the loss of heavy metals such as lead, mercury, *etc*. The production of all these raw materials and the goods made from them would have caused enormous environmental damage through mining, transport and energy use. In fact, recycling 1 kg of aluminium saves 8 kg of bauxite, 4 kg of chemical products and 14 kW of electricity. Therefore consideration of end-of-life treatment will soon become an integral part of product design.

Another major concern is the toxic nature of many substances such as arsenic, bromine, cadmium, lead, mercury and HCFCs, *etc*. Even in the consumer products' category, the number of refrigerators and freezers that are disposed of annually in the UK is 2.4 million units and these units contain gases like chlorofluorocarbons (CFCs) and hydro chlorofluorocarbons (HCFCs) used for cooling and insulation. Both are greenhouse gases, which when released into the atmosphere contribute to ozone layer depletion, leading to climatic changes. The European Council regulation No. 2037/2000 on substances that deplete ozone layer came into effect in October 2001.

Another example of household items is fluorescent tubes, which contain toxic heavy metals such as lead, mercury and cadmium and if these substances enter the human body they may damage liver, kidneys or brain. Mercury is a neurotoxin and can build up in the food chain. A four feet fluorescent tube may contain over 30 milligrams of mercury. The EC permissible limit for mercury in drinking water is one part per billion or 0.001 mg a liter. Here again, we have the ROHS EC directive (2002/95/EC) on hazardous substances.

In fact, end-of-life treatment will become the liability of the manufacturer and distributor of all products eventually. The WEEE directive of the European Union is the first step in this direction at least in the electrical and electronic sector. The WEEE directive (2002/96/EC) as passed by the European Community is aimed to prevent waste electrical and electronic equipment from ending up in landfills and to promote the level of recycling and reuse in the electrical and electronic sector. This directive requires all manufacturers and importers of electric and electronic equipment to meet the costs of collection, treatment and recovery of their waste electrical and electronic equipment at the end of their useful life.

The waste generated in this sector is not small either. For example, in a small country like Ireland, an estimated 35,000 to 82,000 tonnes of waste electrical and electronic equipment was generated in 2001. This amounted to 9 to 18 kg per person. Each year, more than 100 million computers are sold and over 1 million computers are disposed of in landfill sites. The rest are recycled for parts or material. Ecomicro – a recycling company in Bordeaux, France is reported to resort to recycling of components out of 1500 tonnes of obsolete or unusable computers annually. In fact, the market for refurbished computers has increased by 500% since 1996 but less than 20% of all discarded computers are recycled. Currently, a total of 40%, which is 1.5 million printer cartridges, are recycled annually.

1.6 Futuristic System Designs

One of the ways of arresting environmental degradation is to discard old polluting technologies and production processes. The other way of slowing down the environmental degradation would be to prolong the life span of all products and systems so that we conserve energy and materials to satisfy our needs when reckoned over a given interval of time. In other words, the old principle *use and throw,* which was considered indispensable to keep the wheels of industry running and for economic prosperity of nations has eventually given way to the philosophy of reuse, recycle, and conservation if we do not intend to damage the life support system [3], of planet Earth. In short, we must be able to design highly reliable products and systems. Earlier reliability of products and systems was considered an economic compulsion to remain in business and to compete in the market but now it also an environmental compulsion

Other pathways to achieve sustainable products and systems and to minimize environmental impacts would be to use the concept of *industrial ecology,* which would entail clustering selected industries and have their *inputs* and *outputs* interlinked and mutually supported in order to preserve and conserve energy and materials including waste. We have also to work out methods of efficient energy generation and utilization, cleaner transportation, and improved materials. The use of biotechnology for improving products and cleanup process for taking care of effluents, extensive use of biodegradable materials and plastics would have to become quite common in future to prevent environmental degradation. Molecular manufacturing is being seen as clean process and a potential pathway for developing sustainable products and systems.

Several industrialized nations are taking a lead in the development of future products, processes, systems and services that are not only environmentally benign but have the advantage of economy and efficiency. Instead of mining; recycling, recovery and reuse are all becoming more and more common, as these are not only cost effective but less energy intensive and less polluting. Waste minimization, waste processing and safe disposal while conserving natural resources, the optimum and efficient use of energy including natural sources of energy, product and process, eco-friendly designs and improvement of performance of systems, for longevity and conservation of resources, are becoming increasingly important means of achieving sustainable products and systems.

Due to the existing fierce competition and improving technologies, modern systems are becoming more and more reliable than before. Today, we must recognize that unless we integrate the concept of economy reflected through material, resources and energy audit with performance audit reflected through quality, reliability, safety audits and finally with the environmental audit for sustainability, we would only be having wasteful and imperfect system designs. Therefore, it is time that we take the initiative in making system designers visualize the linkages or interdependence between environment, economy and performance.

Design for end-of-life requires manufacturers to reclaim responsibility for their products at the end-of-life. The alternatives to landfill or incineration include: maintenance, recycling for scrap material, and remanufacturing. This is shown in Figure 1.1.

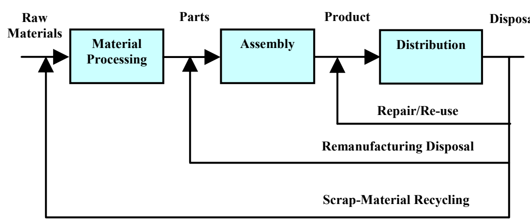

Figure 1.1. End-of-life options

Maintenance extends product life through individual upkeep or repair of specific failures. Remanufacturing is a production batch process of disassembly, cleaning, refurbishment and replacement of worn out parts, in defective or obsolete products. Scrap material recycling involves separating a product into its constituent materials and reprocessing the material. Remanufacturing involves recycling at parts level as opposed to scrap material level. It is actually in effect recycling of materials while preserving value-added components. Remanufacturing also postpones the eventual degradation of the raw materials through contamination and molecular break down, which are the characteristics of scrap material recycling. Since remanufacturing saves 40–60% of the cost of manufacturing a completely new product and requires only 20% energy, several big companies are resorting to remanufacturing. Xerox is an example of this case. IBM has also established a facility in Endicott, New York as a reutilization and remanufacturing center. UNISYS and Hewlett Packard also use this strategy. It must, however, be stated that remanufacturing is not suitable for all types of products; it is appropriate only for those products that are technologically mature and where a large fraction of the product can be used after refurbishment.

It should be mentioned here that a designer must account for the various costs associated with recycling and remanufacturing including the first cost, recycling cost, and the cost of failure during disassembly and reassembly. The first cost is the cost of manufacturing and the first assembly. Recycling cost includes the cost of extracting material or cost of separating parts of different materials. Both maintenance and remanufacturing involve disassembly and reassembly and part reuse and failures can occur during these phases. Therefore, the consequences of the above failures are weighted by their probabilities of occurrence. For example, rivets and welds are usually destroyed during the disassembly. Another part of the cost includes the cost of a part being damaged during assembly or disassembly. Cost also includes the cost of damage caused to a part when a fastener is extracted. Maintenance costs are the costs associated with disassembly or assembly, whereas the remanufacturing cost is the total cost under all the mentioned heads.

While modeling for reliability, an analyst will have consider the fact that for a product or system with brand new components, we usually assume that the population size is constant and has the same probability density function $f(x)$. In remanufactured systems, part failure results in replacement of a part of the same type or different type. The remaining system remains unchanged or is reconfigured to accommodate the replaced part. Thus there are two different failure density functions to consider. Also the age distributions of each of the part populations are tracked to determine the reliability of the composite system population.

In short, prudence in designing systems that have less environmental consequences is the necessity of today. Longer life or durability with less pollution is also economically beneficial in the long run and would yield minimum life-cycle costs. The criterion of sustainability for judging the performance of system would imply less pollution, optimum utilization of materials and energy, waste minimization and a longer life for the system and above all minimum risks to our life support system. This would also be an economic proposition as *sustainability* is interlinked with other performance attributes.

1.7 Performability

In search of a simple, suitable and appropriate term for reflecting this new concept, several terms defined from time to time were explored but none was found more appropriate than the term *performability*. In 1980, John Meyer [4] introduced the term *performability* in the context of evaluation of highly reliable aircraft control computers for use by NASA. Originally, Meyer [4] used this term mainly to reflect attributes like reliability and other associated performance attributes like availability, maintainability, *etc*. However, this reflected only partially the performance measures that we now would like the word to mean. Also, since that time dependability has been used to include more attributes related to performance. Therefore, it was considered logical and appropriate to extend the meaning of performability to include attributes like dependability and sustainability.

Thus, the definition of the term *performability* has been widened to include sustainability in the context of the changed scenario of the 21st century in order to reflect a holistic view of designing, producing and using products, systems or services, which will satisfy the performance requirements of a customer to the best possible extent and are not only dependable (implying survivability and safety) but are also sustainable.

1.8 Performability Engineering

Performance engineering can be defined as the entire engineering effort that goes into improving the performance of a system that not only ensures high quality, reliability, maintainability and safety but is also sustainable.

Implicit with this definition is not only the high performance of a system but also its minimum life-cycle costs. Performance engineering addresses sustainability along with other factors like quality, reliability, maintainability, and safety. We cannot separate environmental problems from the economics of clean production and clean technologies. Likewise, improved performance should necessarily imply less environmental pollution, less material and energy requirements, waste minimization, and finally conservation and efficient utilization of available resources, which in turn result in minimum life-cycle costs. These problems are best tackled at the design stage of a system.

When an aggregate attribute such as *performability* reflects a designer's entire effort in achieving sustainability for a dependable product, we could call this effort *performability engineering*, which in other words is meant to reflect the entire engineering effort of a producer to achieve the performability of a product, system or service, which in fact can be called improving 3-S, namely, survivability, safety and sustainability. This concept is depicted in Figure 1.2. It may be emphasized here that the usual definition of dependability ignores the accompanying environmental consequences while creating products, systems and services. It is evident that in order to produce a truly optimal design economically, consideration sustainability should not be overlooked. These attributes are very much influenced by the design, raw materials, fabrication, techniques and manufacturing processes. They are interrelated and reflect the level or grade of the product so designed and utilized which is expressed through dependability.

The life-cycle activities of a product or system are depicted in Figure 1.3. Performability takes a holistic view of various activities and processes and takes stock of what is being produced and what is being wasted. We conserve and economize materials, energy, avoid waste to optimize a product or system's design over its entire life cycle.

In fact, performability engineering not only aims at producing products, systems and services that are dependable but involves developing economically viable and safe processes (clean production and clean technologies) that entail minimal environmental pollution, require

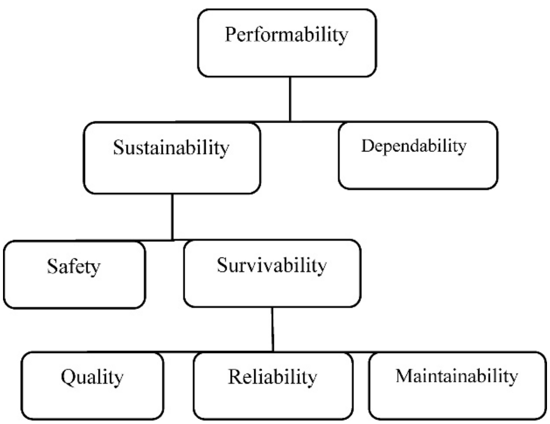

Figure 1.2. Implication of performability

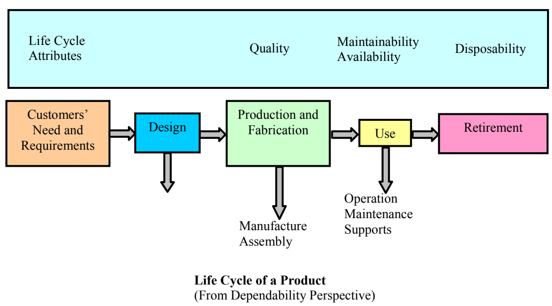

Figure 1.3. Life-cycle activities

minimum quantities of raw material and energy and yield safe products of acceptable quality and reliability that can be disposed of at the end of their life without causing any adverse effects on the environment. The WEEE directives of the European Community are a step this direction.

This would also necessitate the efficient use of natural resources and the use of non-waste technologies, which would ensure that all raw materials and energy are used in a most rational and integrated way to curb all kinds of wastages while maximizing the performance.

Obviously, less material and energy consumption, either through dematerialization, reuse or recycling or through proper treatment (clean up technology), would lead to a lesser degree of environmental degradation. Similarly, a better design would result in prolonging the life span of a product and hence would ensure less adverse effects on the environment over a given period of time. In other words, we must integrate the entire life cycle of activities of survivability with that of environmental cycle considerations to improve the product or system performance within the technological barriers with minimum cost.

At every stage of the life cycle of a product, be it extraction of material, manufacturing, use or disposal, energy and materials are required as inputs and emissions (gaseous, solid effluents or residues) and these influence environmental health of our planet.

Unless we consider all these factors, we cannot call the design of products, systems and services truly optimal from an engineering point of view. This necessitates bringing synergetic interaction between the constituent areas of performability.

1.9 Conclusion

Long-term product, system or service development strategies necessitate the consideration of performance attributes like performability, which takes a holistic view of the entire life-cycle activities and their influence on our environment and in fact on our own existence and that of future generations on this planet. Truly optimal design should necessarily consider sustainability along with dependability as the design criteria for all future products, systems and services.

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