ROLE OF PERFORMANCE ENGINEERING IN SUSTAINABLE DEVELOPMENT

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Summary

One of the important strategies of implementing sustainability is to prevent pollution and this cannot be viewed in isolation with the fact that a good product or system performance would necessarily entail less environmental pollution because of its inherent longevity and implicit optimum utilization of material and energy in a limited resources scenario. Naturally, this strategy is also an economic proposition. In other words, sustainability depends heavily on the performance characteristic of a product, system or service. Therefore, the objective of this article is to draw the attention of environmental scientists, engineers and economists, to incorporate the requirement of performance improvement in all future sustainability planning and design programs.

Some of these concepts presented here may have been known, but are included to provide a holistic view of the problem for effective implementation of performance improvement program in order to realize the goal of sustainable development.

1. Introduction

It is true that no development activity for the benefit of human beings can possibly be sustained without incurring a certain amount of risk. In simple terms, the risk is the chance of loss, injury or death. The chance is usually assessed through probability and the loss in terms of consequences, which may be in terms of environmental degradation that may include pollution of land, water, air, depletion of resources, cost of replenishment or restoration to acceptable levels both during normal operating conditions, or under the conditions of sudden hazardous releases due to catastrophic failures or accidents. While some hazards are created by humans, by the introduction of new technologies, products or chemicals, there are others forced on humans, by external events or natural disasters. In the past, we have witnessed several technological (human-engineered) disasters, which had their origin in our underscoring the importance of ensuring the best level of system performance and its linkages with environmental risk, which must be evaluated in terms of benefit and cost.

Risk is fundamentally intertwined with the concept of probability of occurrence of hazards and consists of seeking answers to the following questions:

(a) What can go wrong that could lead to an outcome of hazard exposure?
(b) How likely is this to happen?
(c) If it happens, what consequences (long or short) are expected?
(d) Risk is usually categorized by the nature of the consequences that are being investigated, for example:
   (i) Societal risk (or public safety, when referred to large groups of people that may be affected by, say, an earthquake or major release of toxic chemicals);
   (ii) Individual risk (or individual safety);
   (iii) Occupational risk;
   (iv) Environmental/ecological risk;
   (v) Economic risk;
   (vi) Social risk.

Quantitative risk assessment usually involves an estimation of the degree or probability of loss. Risk assessment, according to McCormick, includes three stages. These are: risk identification (the recognition that a hazard with definable characteristic exists); risk estimation (the scientific determination of the nature and level of the risks); risk evaluation (judgement about acceptability, or otherwise, of risk probabilities and consequences).

After a risk has been identified, estimated or evaluated (or any combination of the three), there comes a point where some kind of intervention (or deliberate decision not to intervene or to delay action) must be made. What is the course of development that is "safe enough"? A safe or less risky, course of development would be one compatible with the environment—and can be called eco-development. It would not only minimize or reduce the undesirable side-effects to acceptable levels, for those subject to risk, but also for those who create risks and those responsible for managing them. There is always a cost attached to the risk and the benefits flowing from a project or plant. Therefore, one has to work out the risk/benefit ratio. In considering risk/benefit trade-offs, it is essential to remember that for every benefit, we usually incur some risk or cost, however small it may be.

Chemical industry is mainly responsible for handling or producing toxic substances. Every chemical and chemically related substance, if misused, or misapplied or improperly disposed of, can produce some degree of risk. This is true throughout the cycle of synthesis, production, handling, transportation, use, and ultimate disposal. Usually a risk assessment in such cases will focus on a particular aspect of a toxicant's production, use, storage, or disposal. There is always a possibility and likelihood of a toxic substance being released to the environment due to an accident. A preliminary description of the exposure scenario in such cases addresses the following questions:

- Where, when and how can the release of the toxicant occur?
- What is the immediate vicinity of the release?
- What are the quantity, physical state and chemical composition of the released material?

After the preliminary information has been obtained with respect to the exposure scenario, the following additional information is required:

- What are the concentrations and duration of exposure in the area of the toxicant's release?
- Will the toxicant be distributed to a larger area, and if so, what will be its form (physical and chemical), concentration, and duration of residence throughout the area of distribution? This description should include the concentrations at various locations and times throughout its residence, and it should include air—and waterborne materials as well as those taken up by biological materials, such as plants and animals.

Basic chemical and physical characteristics of the material, which may be relevant to its toxicity, include chemical composition, melting point, boiling point, density, molecular weight, and its mixture and reactivity with other materials present in the exposure environment.

Environmental Risk Assessment can be distinguished from hazard assessment, in that risk assessment employs a scientific method to assess probabilistic of specified effect, whereas hazard assessment depends more on the margin of safety and the expert judgment of assessor. While both hazard and risk assessment involves integration of exposure and effects assessment, risk assessment also contains estimates of probability of adverse effects. Environmental risk assessment is a balancing or trading-off process, in which various combinations of risks are compared and evaluated against particular social or economic gains. The risk assessment paradigm includes hazard identification, dose exposure assessment, exposure assessment, and risk characterization.

Risk, safety, and environmental consequences, are closely related to system performance and their inter-relationship must be understood to ensure that no undesired incident takes place during the operative phase of the product, system, plant or services. As the modern systems become more and more complex, their chances of failure-free operation also decrease and we cannot possibly altogether eliminate a failure within a system, but the best we can do is to minimize its impact. High-risk systems particularly require a thorough investigation or analysis to ensure high level of performance in order to save the surrounding environment from the catastrophic degradation, once an accident has taken place. All technological catastrophes from the past indicate that had we cared to improve the performance of plants, systems and products and their designs to ensure a very low value of risk, the ecological consequences or impacts of the accidents involving them would have been less damaging. Through better performance, we can always minimize the ecological impacts and associated losses.

2. Generic Causes of Accidents

A complex system, or a plant often constitutes a multitude of several kinds of subsystems. It is a failure of some small part somewhere in a plant or system that often leads to an accident of enormous consequences. In reality, a wide variety of failures, errors and events can occur in complex potentially hazardous plants, and these usually occur on account of logical interactions between human operators and the plant. Some of these interactions can be listed by arguing “why,” “how,” “when,” and “where” of failures. In fact, these interactions can occur at any time of the plant life; viz., during sitting, design, manufacturing, construction, commissioning, and operation.

It is generally believed that accidents occur as a result of failures during plant operations but it is too narrow a view. Failures can occur at any stage of use or operation. For example, it could occur at the time of siting a project. A site is an area within which a plant is located and the local characteristics, such as geological and seismological characteristics and potential for hydrological and meteorological disturbances, can subsequently affect the plant safety. Also, human-engineered hazards, those arising from chemical installations, release of toxic and flammable gases, and aircraft impact can also cause hazards. Air, food chains, and water supplies may provide pathways for possible transport of hazardous materials to humans in an accident situation.

Design errors may be committed in the design and development phase and because of short research, development and monitoring periods, can lead to poor performance of a product. A product deficiency can prove to be very costly once a product design has been released for production and a device is manufactured and distributed. Costs may not only be replacement and redesign costs, due to modifications in manufacturing, procedures, and retraining to enable manufacture of the modified product, but also liability costs, and loss of customer faith in the product.

Defects can be introduced when a plant is fabricated and constructed with deviations from original design specifications and from fabrication/construction procedures. Errors in design, manufacturing and construction stages may persist even after commissioning and demonstration. A simple example of commissioning failures is a software package with bugs.

Failures can occur during any of the following conditions: normal operation, operation during anticipated abnormal occurrences, operation during complex events below design basis, and operation during complex events beyond design basis. Generally, all plants are protected by physical barriers, normal control systems, emergency safety systems, and in-site and off-site emergency counter-measures. For example, an emergency safety system in a nuclear reactor operates when the plant states reach trip set points below safety limits, but above operating ranges. A safety system may also fail in two modes: *fail-safe* and *fail-dangerous*. Accident causation mechanisms can also be split into an *event layer* and *a likelihood layer*. Usually, event and fault trees deal with the event layer. Emphasis is now being placed on the likelihood layer, where management plays a crucial role in managing occurrence probabilities, dependence of event and uncertainties, associated with the events.

Plant safety is constrained by confinement capabilities by physical containments and stabilization of unstable phenomena. Broadly speaking, accidents can be caused either by hardware failures, human errors or external events. Generally, accidents are caused by:

- *Failure of physical containment*: All plants have physical barriers or containment to confine hazardous materials, or to shield hazardous effects. As long as these barriers or containments are intact, no serious accident can take place. It is only when these fail, accidents occur.

- *Failure of safety systems*: All plants have adequate control systems during their routine operations and safety systems and in-site and off-site emergency measures during emergencies. If anything goes wrong with the normal control system, incidents would occur and if emergency safety systems fail to cope with the incident, plant accident would occur. Finally if in-site emergency measures fail to contain the accident, accident invades into environment, and when off-site emergency measures fail to cope with the invasion, serious consequences for public and environment would occur.

- *New Technology*: New technologies although improve system functioning but may introduce some snags during initial burn-in period. Very often complex systems or plants use a large number of components and a failure of few of them can cause an accident.

- *Human Errors*: These are very often the causes of major accidents. Sometimes hardware failures induce human errors, which may lead to an accident. For example, a faulty indicator may cause wrong human intervention to cause an accident. Sometimes, system induced failures occur due to improper management caused by human and hardware failures.

- *Dependent failures*: A chain of failure events can be caused by dependency of failures due to the sharing of common environment or location.

- *External events*: External events, such as fires, floods, lightening, and earthquake are also responsible for causing major plant accidents.

3. Performance Engineering

The ultimate success of an engineering product or a system is often judged by its performance as desired or specified in its design. It is therefore important that while defining the desired performance characteristics of a product or a system, the following, aspects have been considered:

- Definition or objective of a product or system
- Criteria of adequate performance
- Defining boundaries of operating conditions
- Definition of failure or malfunction
- Expected time of operation
- Scope of maintenance and associated conditions
- Tests and sampling procedures.

Generally, the performance of a product can be best described by:

- Capability or the product’s ability to satisfy its functional needs
- Reliability or the product’s ability to continue to function adequately without failures over a specified time and under the prescribed conditions of use
- Maintainability or the product’s ability (if it is a repairable product) to recover to a healthy state following its failure
- Efficiency or the product’s ability to effectively utilize the energy supplied.

These attributes are very much influenced by the design, raw material employed, fabrication, production or manufacturing, or use of the products and reflect the levels to which the product is designed, built and used. Capability and efficiency ensure that design levels are adequate to meet the functional requirements of a product. On the other hand, reliability ensures that the product continues to remain operational over the intended period, and under the specified conditions of use. In repairable products, the ease with which a product can be repaired, maintained and returned to normal operation is assessed by its maintainability. The role that the human factor plays is often determined by various programs and activities that support these attributes of performance, and proper implementation, which leads to a quality product.

It is also true that as the technology changes with time, the performance of products or systems also improves. For example, the performance improvement of digital computers over the last four decades of the twentieth century, has undergone a sea of change, and it is easy to comprehend that starting with vacuum tubes, which has a Mean Time To Failure (MTTF) of 0.5 to 1 h, we have come along way to improve MTTF to 10000 h, using Very Large Scale Integration (VLSI) technology. At the same time, over the same period, we have gained considerably by way of material and energy conservation. In the early 1960s, a digital computer equivalent in performance to a simple PC-XT of 1980s would require several tons of material and would be housed in a big air-conditioned room requiring several hundred kilowatts of stabilized power. By the 1980s, we placed it over our worktable and its power consumption would be equivalent to a 100 W lamp. Today, we have the computing capability of a mainframe computer of 1980s on our desktop, at the same time considerably improved in performance and within purchasing power of an individual.

Obviously, less material and less energy consumption leads to less environmental pollution. It is not only environmentally friendly by way of less material and less energy consumption, but also by way of prolonged life, since reliability of modern computers is much higher than its predecessors, as longer life would mean less pollution over a given period of time period. Also it would be less environmentally damaging in its final disposal after its prolonged use. Therefore, it is no wonder that motivation for reliability or performance improvement, which initially came from economic compulsions, now comes as a compulsion from environmental considerations. Longer life or durability implies less pollution and is also economically beneficial in the long run. Therefore, we should go for high performance products, if the environment is to be preserved.

Performance improvement is usually seen as an instrument for boosting exports of a country through competition in the world market, and primarily as a necessity for economic prosperity. But, as the world resources are dwindling and the cost of raw materials is likely to rise, the quantum of production becoming detrimental to the health of world environment, the emphasis of performance requirement can hardly be underestimated for preserving the environment. A product from the stage of cradle to grave (from the conceptual stage to its disposal or recycle) does degrade the environment. Therefore, we must conserve the raw materials, natural resources and energy that go into the manufacturing of a product. In other words, it is time to go for clean production. Naturally, we cannot possibly reduce the level of use and thus the quantity of these products. Alternatively, we should aim at prolonging the life span of products. That is perhaps the only way left to us to balance the two conflicting factors; increasing demands of ever increasing population and saving earth from further pollution of one type or the other. We must manufacture reliable, energy efficient and cleaner products.

Reliability is an important attribute ensuring high performance of the product, since it directly and significantly influences the product's performance and ultimately its life cycle cost and the economics of its use. Poor reliability in design, manufacturing, construction, and operation would directly increase warrant costs, liabilities, refits, and repair costs. Therefore, performance engineering can be considered synonymous with improving attributes like reliability, durability, quality, availability, safety and efficiency. A product having these attributes is expected to perform well and yield minimum life cycle costs, which not only include design and development costs and manufacturing costs, but also maintenance costs over the product's entire life.

The concept of quality has also undergone several changes which emerged considerably over the last decade of the twentieth century, and even more so at the beginning of the twenty-first. Earlier, the emphasis was focussed on product; that is, quality meant a product's ability to conform to specifications. ISO standard 8402 explains critical terms relating to quality. Quality is defined as: "The totality of features and characteristics of a product or service that bear on its ability satisfy its stated or implied needs." This approach, while acceptable, did not incorporate many of the latest interpretations of quality. Later on, its definitions started to incorporate the customer, and quality is now defined as anticipating and exceeding customer expectations. The concept of quality has evolved to recognize the importance of satisfying an organization's many stockholders, including community, suppliers, shareholders, employees and management. Quality today includes such diverse elements as improving work life, promoting work place, diversity, bettering environmental conditions, facilitating trade, and enhancing competitiveness.

Two additional concepts in vogue today, are quality systems and total quality management. Quality system is defined as: "The organizational structure, responsibilities, procedures, processes and resources needed to implement quality management." ISO standard 9000 specifies the requirements for quality systems. Total Quality Management (TQM) is defined as: "A management approach to an organization centered on quality, based on the participation of all its members and aiming at long term success through customer satisfaction and benefits to the member of the organization, and to society." Long-term success through customer satisfaction must be an organization's goal and should be predicted on the pursuit of quality. Everyone's participation and value to society should be the motto. Customer's requirements are first be identified, defined, and clarified, and procedures and systems are then established to monitor, control and improve those factors that directly and indirectly are involved in the production of uniform products and the delivery of consistent services. Learning from the experiences of the Japanese, the American industries also came around to this idea and subsequently Motorola, Xerox, IBM, etc. soon built up envying reputations for their products. With this was born the quality revolution of the 1960s. Starting as a natural rubber producing country in 1950s, Malaysia today is the second largest producer of microelectronics chips. Open any personal computer chassis, one can find a host of chips being used in its circuitry, manufactured in Malaysia, all this was possible for this south-eastern country by inculcating the culture of quality, and in particular the country's recourse to performance consciousness.

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Biographical Sketch

Krishna Behari Misra has held the position of a full professor since 1976, and is with the Reliability Engineering Center, which was founded by him, and where a master's degree program in "reliability engineering" was conceptualized and started for the first time in India. This center is at the Indian Institute of Technology, Kharagpur, where he also served as Dean, Institute Planing and Development. He has been Director of NERIST (1995–1998), and Director-grade-Scientist at the National Environmental Engineering Research Institute, Nagpur (1992–1994). He worked in Germany at GRS-Garching, Technical University-Munich, RWTH-Aachen, Kernforschungszentrum-Karlsruhe, and visited several European countries and the US, on invitation.

He has published over 175 papers in international journals, e.g., *IEEE Transactions on Microelectronics and Reliability*, *International Journal of System Science*, *Reliability Engineering and System Safety*, *International Journal of Quality and Reliability Management*, *Fuzzy Sets and Systems*, etc. He has served on editorial boards of several international journals. He authored an 889-page book "*Reliability Analysis and Prediction: A Methodology Oriented Treatment*," published by Elsevier Science Publishers, in 1992. In 1993 and 1995, he edited a 715-page book, *New Trends in System Reliability Evaluation*, published by Elsevier, and an 853-page book, *Clean Production: Environmental and Economic Perspectives*, published by Springer Verlag.
He is a fellow of the Indian National Academy of Engineers, Indian Academy of Sciences, IETE (India), IE (India) and SaRS (UK), and is the recipient of *Lal C. Verman Award* in 1983 "*for his pioneering work in Reliability Engineering in the country*" and of a plaque in 1995, from the IEEE Reliability Engineering Society of US in 1992 "*in recognition of his meritorious and outstanding contributions to the field of Reliability*." He is Chairman of the LTDC-3 Committee of Indian Bureau of Standards. He served as a member of the Environmental Appraisal Committee (for nuclear power plants in India) and as Convener of the NCST working group on Reliability Engineering in India, set up by DST, Government of India.