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Integrated framework to optimize RAM and cost decisions in a process plant

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ABSTRACT

The research implications of reliability, availability and maintainability (RAM) aspects of engineering systems in recent years have increased substantially due to rising operation and maintenance costs. To strike a balance between the two the paper presents a framework which makes use of both qualitative and quantitative techniques to optimize RAM and cost decisions in a process plant. In the quantitative analysis, the imprecise and vague information regarding the system failure behavior is quantified by using the principles of fuzzy mathematics in terms of fuzzy and crisp values. Further, to manage the system reliability for best economic performance a resource optimization model based on multi-stage decision making (MSDM) has been proposed. The model makes use of crisp output values of unit's reliability along with relevant system information (number of components, manpower, cost ranges). In the qualitative analysis the in-depth analysis of the system is carried out using Root Cause analysis (RCA) and Failure Mode & Effects Analysis (FMEA). The ambiguities associated with the traditional FMEA are handled using Fuzzy Decision Making System (FDMS) and Grey Relation Analysis (GRA). The suggested framework has been illustrated with the help of a case.

1. Introduction

Growing intricacy of systems as well as rapidly increasing Operation and Maintenance (O&M) costs incurred due to loss of operation as a consequence of sudden or sporadic failures have brought to the forefront the RAM (Reliability, Availability and Maintainability) aspects associated with Production and operation management (POM) systems. The significance of reliability, availability and maintainability (RAM) in recent years has increased due to rising energy cost and the competitive market environment (Sikos & Kleme, 2010a). The expectation today is that complex equipment and systems should not only be free from defects and systematic failures but also perform the required function for a stated time interval and should have a fail-safe behavior in case of critical or catastrophic failures. As far as system reliability is concerned, it has been established as a useful tool for safety and risk analysis, production availability studies and design of production systems (Adamyan & David, 2004; Aksu & Osman, 2006; Aneziris & Papazoglou, 2004; Vallem & Saravannan, 2011). Availability has been considered as significant measure of performance for many engineering systems which are generally considered as repairable ones (Cochran, Murugan, & Krishnamurthy, 2000; Juang, Lin, & Kao, 2008). To this effect the knowledge of behavior of the system, their components are customary in order to plan and adapt suitable maintenance strategies. Thus, maintainability is also to be considered as a key index to enhance the performance of POM systems (Madu, 2005; Nepal et al., 2007; Sharma & Kumar, 2008; Sikos & Klemes, 2010b).

Recent advances in technology have made the job of reliability/system analyst(s) more challenging as they have to study, characterize, measure and analyze the behavior of system using various qualitative and quantitative techniques (Adamyan & David, 2004; Aksu & Osman, 2006; Cai, 1996; Hauptmanns, 2011; Hu, Si, & Yang, 2010; Iraklis, Osman, & Seref, 2010; Modarres & Kaminski, 1999; Sharma & Kumar, 2008; Vallem & Saravannan, 2011). One can observe various kinds of failures in past under various circumstances such as nuclear explosions (Chernobyl nuclear disaster, 1986); Industrial plant (oil pipeline at Jesse Nigeria, 1998); aeroplane crashes, and electrical network shutdowns etc which may be due to human error, poor maintenance, inadequate testing/inspection. But, failure is nearly an unavoidable phenomenon with engineering systems/components which requires the knowledge of precise numerical probabilities and component functional dependencies, the information which is relatively difficult to obtain. Even if data is available, it is often loose and thus, subjected to certain degree of imprecision. Further age, adverse operating conditions and the vagaries of manufacturing/production processes affects

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Nomenclature

Acronyms

A_{sys}	Availability
R_{sys}	Reliability
O_f	Probability of failure occurrence
O_d	likelihood of non-detection
S	Severity of failure
ENOF	Expected numbers of failures
FA	Failure analysis
FM	Fuzzy Methodology
FIS	Fuzzy Inference system
FDMS	Fuzzy decision-making system
FTA	Fault Tree Analysis
FRPN	Fuzzy risk priority number
FMEA	Failure modes and effects analysis
GRA	Grey Relation Analysis
RAM	Reliability, availability, and maintainability
RPN	Risk priority number
RCA	Root cause analysis
MSDM	Multi-stage Decision Making
MTTR	Mean time to repair
MTBF POM	Mean time between failures Production and Operations Management

Quantities

R_J	Reliability of successful operation
C_s	Cost of sales
F_1	Coefficient for component cost
F_2	Coefficient of manpower cost
M, N	crisp numbers
$\tilde{M}, \tilde{N}$	Fuzzy numbers
$\mu_{\tilde{M}}(x)$	Membership function of M In fuzzy set $\tilde{M}$
C_j	Resource allocated to the activity j

Greek Symbols

λ	Failure rate
τ	Repair time
$\lambda_{(\alpha)}, \tau_{(\alpha)}$	Intervals for fuzzy failure rate and repair time
λ_{ij}, τ_{ij}	Fuzzy failure and repair time of component i with $j = 1$ being lower mean and upper bounds respectively
β_k	Weighting coefficient
ε	State function (Total resource allocation)
ε_0	Optimal resource allocation
λ	Lagrange's multiplier (Budgeting coefficient)

each part/unit/of system differently. The traditional analytical techniques (mathematical & statistical models) not only needs large amount of data but also it is difficult to obtain because of numerous constraints i.e. rare occurrence of event failures (only a few per million hours of operation), human errors and economic considerations (Sergaki & Kalaitzakis, 2002; Sittithumwat, Soudi, & Tomsovic, 2004).

When modeling the RAM aspects of POM systems one comes across many different uncertainties which can be grouped with regard to their causes into two types: (i) aleatory and (ii) epistemic uncertainties (Helton & Burmaster, 1996). Aleatory uncertainty is caused by random variations in samples and is also known as stochastic, type A or irreducible uncertainty. Epistemic uncertainty is caused by lack of knowledge about a system or phenomenon and is also known as subjective, type B or reducible uncertainty. Different mathematical tools can be used to treat these two types of uncertainties. *It is a common opinion that both types of uncertainties can be treated with Bayes' theorem (Cizelj, Mavko, & Kljenak, 2001; Parry, 1996). Complex systems may have both kinds of uncertainty. Zadeh (1995), Cizelj et al. (2001), Ross, Booker, and Parkinson (2003), and Görkemli and Ulusoy (2010) have stated that probability theory can be used in concert with fuzzy set theory for the modeling of complex systems. Based on the mature scientific theory, the probabilistic methods deals with uncertainty which is essentially random in nature but of an ordered kind. For instance, Bayesian methodology appeared in late 1970s is widely used in probabilistic risk assessment, an exercise aimed at estimating the probability and consequences of accidents for the facility/process under study (Aven & Kvaloy, 2002; Siu & Kelly, 1998; Vaurio, 2005). Bayesian statistics provide a natural framework combining random and nonrandom uncertainty so fuzzy Bayesian methods are developed for the solutions of the reliability problems*. The non-probabilistic/inexact reasoning methods on the other hand study problems which are not probabilistic but cause uncertainty due to imprecision associated with the complexity of the systems as well as vagueness of human judgment. These methods are still developing and often use fuzzy sets, possibility theory and belief functions. *Introduced by Zadeh (1965) Fuzzy set theory is used to deal with problems in which the absence of sharply defined criteria is involved and has been considered in literature by various researchers as a modeling language to approximate situations in which fuzzy phenomena and criteria exist. Using a term principle of incompatibility, Dr. Zadeh states "As the complexity of a system increases, our ability to make precise and yet significant statements about its behavior diminishes until a threshold is reached beyond which precision and significance (or relevance) become almost mutually exclusive characteristics" (Zadeh, 1973). The theory has been commonly used for imprecise information in a non-probabilistic sense and allows integration of information of various parameters into the modeling and evaluation framework. The imprecise parameters can be expressed as fuzzy numbers and the variability is characterized by the membership function (MF) which may be triangular or trapezoidal as the most common MF types used in reliability application are triangular or trapezoidal functions (Yadav, Singh, Chinnam, & Goel, 2003).* As an emerging methodology, it helps to incorporate imprecision and subjectivity into the model formulation and solution process. By allowing for imprecision in the model, fuzzy logic opens the possibility for the inclusion of imprecise inputs and imprecise thresholds (Homayouni, Hong, & Ismail, 2009).

For example, Lin and Wang (1997) combined fuzzy set theories with expert elicitation to evaluate failure probability of basic events of a robot drilling system, based on triangular and trapezoidal MFs. Sii, Ruxton, and Wang (2001) presented a novel risk assessment technique based on fuzzy reasoning for maritime safety management system. Sergaki and Kalaitzakis (2002) in their work developed a fuzzy relational database model for manipulating the data required for criticality ranking of components in thermal powers plants. Hauptmanns (2004) applied semi-quantitative fault tree analysis for process plant safety by computing frequency and probability ranges using fuzzy methodology. Liu, Yang, Wang, and Sii (2005) in their work proposed a framework for modeling, analyzing and synthesizing system safety of engineering systems on the basis of rule based inference methodology using evidential reasoning. The framework has been applied to model system safety of an offshore and marine engineering system. Yadav et al. (2003)