RELIABILITY ASSESSMENT TOOLS FOR MULTI-COMPONENT COMPLEX SYSTEMS: AN OVERVIEW

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ABSTRACT

The global business competitiveness has increased the challenges of industries having multi component complex systems to deliver their products as well as services both, on demand maintaining their quality standards. This paper discusses the scope of reliability, availability and maintainability (RAM) assessment tools which includes qualitative and quantitative methods and commercially available software's which might be quite helpful in reducing the fear of uncertain failures and their effects on overall performance. The integration of RAM tools in conceptual and complex process design will assist managers to select an optimum maintenance policy, requirement of spare parts, software tools, keeping in mind the various factors such as operational environment, skill of operator's etc. and comply with other environmental requirements. We draw some conclusions about the degree to which different classes of problem have been solved, and discuss challenges for the future.

Key words: ***RAM tools, Complex Systems***

I. INTRODUCTION

1.1 Background

A Failure is the key to origin of word Reliability. Of course many failures are much more significant in both their economic and safety effects. For example, Gas leakage tragedy happened in Bhopal (India).The incident was attributed to a faulty operation and maintenance procedure resulted into loss of thousands of lives and many permanent disabilities. A long list of such failures and significant effects on safety and economy has now become a positive lesson for the modern industry leaders. In the present global business scenario, where competition is increasing and profit margins are becoming slimmer, the attention of the industry leaders has turned to implement the RAM tools to find ways of developing reliable products and services with costs savings and improved productivity. An estimate says, revenue lost due to unexpected shutdowns of plant can range from \$500-\$100000 per hour (Tan and Kramer, 1997). For refineries the cost of unplanned shutdowns could come to millions of dollars per day (Nahara, 1993). According to a recent market forecast (HPI Market Data book 2014), the total hydrocarbon processing industries spending on capital, maintenance, and operating budgets is expected to exceed \$77 billion in the U.S. and more than \$280 billion globally in financial year 2014, a significant increase over the past several years. Further, the refining industry has announced a large volume of capital and maintenance projects over the next 3 to 5 years to expand capacity to meet demand drivers and maintain the extensive, aging infrastructure. In, 2003 it was forecasted to reach $44.9 billion of which $11.4 in the United States alone, and the majority on the Gulf Coast. Spending for equipment and materials represents 40% of the maintenance budget and will reach almost $18 billion in 2003. Labor costs account for the other 60% (almost $27 billion) of the maintenance budget. Although these figures do not include the cost of interruption due to unplanned failures. According to another estimate (Williams, 2001), typical opportunities for profitability improvement using RAM tools. in the case of petroleum refinery operations range from 0.10 - 0.20 US$/bbl while in the case of a poor performer the range can increase to 1.0- 2.0 US$/bbl range with any capital investment. To get some perspective on the scale of saving, for a typical petroleum refinery with a throughput of about 30000 bbl/day, or roughly 198 m3/hr, the saving could be in the range of about 1-2 million US$/year while for poor performers it could be in the range of 10-20 million US$/year. The aforementioned figures provides a direction for implementing different reliability engineering tools to increase the operational effectiveness of existing petrochemical plants and refineries around the world(Goyal,2004). Some of the success stories have listed in TABLE 1 that can be extracted from company's internal magazines, corporate websites and their annual reports. These examples point to the growing attention given in industry to using reliability engineering tools to squeeze profit from their existing facilities [9].

TABLE 1

Company	Benefits
Marathon Ashland Petroleum	Saved $3 million lost opportunity costs in one year by avoiding heat exchanger failures at a total cost of about $500,000
ExxonMobil	The reliability and maintenance system program, since its introduction in 1994, has reduced maintenance costs (about $1 billion) by about 30% while improving mechanical availability by about 2%
Shell's Pulau Bukom refinery	The design and operational medications made during 1996 turnaround results in a four year run of its long-residue catalytic cracking unit (LRCCU) with only 21 hours of downtime
Toa refinery, Japan	With the help of Shell Global Solutions International BV's maintenance and reliability (Merit) program saved $10 million in its first year and $17 million in the second year
Lima refinery	Over $1.4 million dollars per year were saved in pump repairs by increasing the MTBF (Mean time between failure) of the pumps
Conoco Refinery	Maintenance costs dropped by 21% and unscheduled lost profit opportunities were down 47% ($34 million) due to improved equipment reliability and streamlined maintenance practices

In literature a number of review papers have appeared in the last few decades that provide a detailed survey of topics that include reliability-availability analysis methods (Dhillon and Rayapati, 1988; Lie et al., 1977; Sathaye et al., 2000), reliability optimization (Kuo and Prassad, 2000) and, maintenance optimization (Dekker, 1996; Dekker and Scarf,1998). More detailed information on these topics can be found in standard reliability engineering textbooks such as Ebeling,C.E.,(2010), Kuo et al. (2001). Henley and Kumamoto (1992) and Billinton and Allan (1992).

1.2. Terminology and Relations of RAM Tools

The RAM stands for Reliability, Availability and Maintainability. This can be used as an indicator to describe the performance of a plant. The reliability engineering discipline provides industry with necessary concepts and tools to improve its economic performance by increasing the effective utilization of its manufacturing assets.

Reliability is the ability of an item to perform a required function, under given environmental and operational conditions and for stated period of time (BS4778,1991). Reliability of the equipment that fails randomly can be calculated by the following formula:

R (t) $=e^{-\lambda t}$, λ=Item failure rate,

t =Intended mission rate

Availability, in general, is defined as the ability of an item to perform its required function at a stated instant of a time or over a stated period of time (BS4778, 1991) BS4778, 1991. Glossary of terms used in quality assurance including reliability and maintainability terms. British Standards Institution, London.). Availability can be calculated by the formula: (Dhillon 2006)

$$A = \frac{\text{Planned production time} - \text{Shutdowns}}{\text{Planned production time}} * 100\ \%$$

Maintainability is the ability of an item, under stated conditions of use, to be retained in, or restored to a state in which it can perform its required functions when maintenance is performed under stated conditions and using prescribed procedures and resources (BS4778, 1991).Plant availability is a function of the reliability and maintainability characteristics of a plant. Sourabh et al (2011) presented the relation between reliability, availability and maintainability (RAM), with the help of Fig. 1.

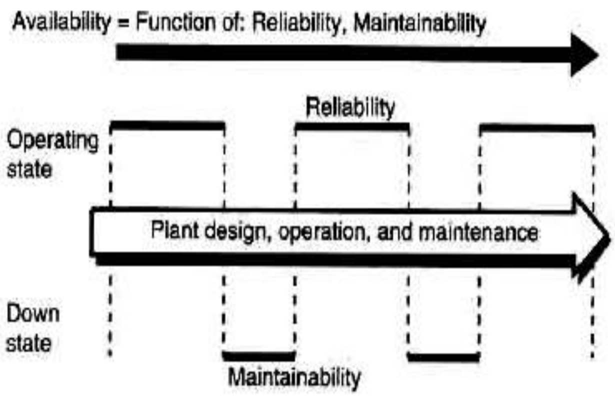

Fig.1 Relationship Between Reliabilty, Availability & Maintainability

II. STRUCTURE OF RAM TOOLS

Kostina et al [15] proposed a structure of reliability estimation tool used in process industries includes three main parts (Fig. 1):

1. Reliability analysis module – the main part;
2. Design-level part for process analysis;
3. Analytical part.

Every part is considered on the following levels:

- Standard methods for reliability assessment;
- Additional activities for reliability assessment;

- Extended reliability analysis.

The standard methods used in this tool are based on an international standard proposed in Electronic Reliability Design Handbook [18]:

- Failure Mode and Effects Analysis(FMEA),
- Fault Tree Analysis (FTA),
- Mathematical Reliability Prediction (RP).

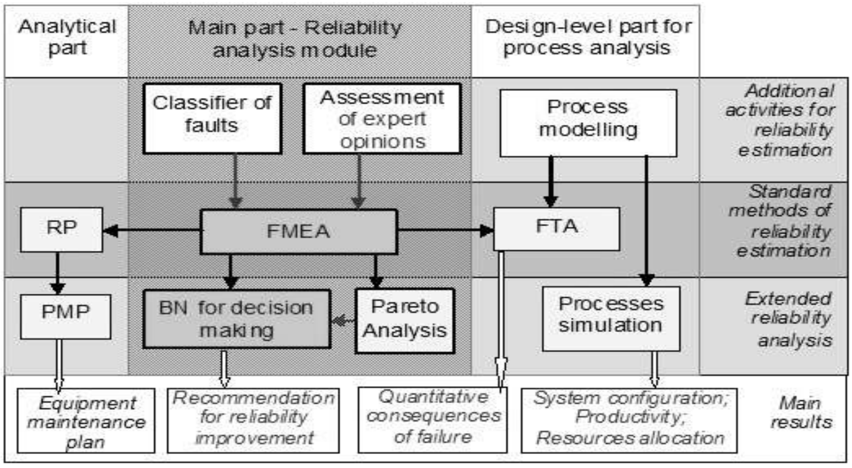

Fig.2.Structure of Reliability Estimation Tool Used in Process Industry

Work of this tool is based on Failure Mode and Effects Analysis (FMEA) method which is combined with Belief Bayesian Networks (BBN). The tool developed to analyze a production process enables companies to analyze the process as a whole and its parts and get an efficient prognosis for the production process reorganization.

Software tools: A numbers of computer software's (commonly called decision support tools) are commercially available which supports process engineers in solving problems like data collection/analysis and even more complex problems such as spare parts optimization, preventive maintenance scheduling etc. Like any other engineering support software, these tools can be expensive and will probably require a significant investment. These software tools can be classified broadly as (i) Monte Carlo Simulation based, (ii) Analytical based, and (iii) Hybrid based. A list of some commercially available computer software's is presented in TABLE 2 [8, 9].

TABLE 2

Software	Type	Manufacturer/License provider
BlockSim	Hybrid	ReliaSoft Corporation, 115 S. Sherwood Village Drive, Suite 103, Tucson, AZ 85710
AvSim	Simulation	Item Software, Inc., 2030 Main Street, Suite 1130, Irvine, CA 92614
TITAN	Simulation	Fidelis Group, 4545 Post Oak Place STE 347 Houston, TX77027
SPAR	Simulation	Clockwork Designs, Inc., 3432 Greystone Drive, Suite 202, Austin, TX 78731
SPARC	Analytical	IES Products 2811 NV Reeuwijk Reeuwijkse Poort 301 The Netherlands
MIRIAM	Simulation	EDS-Scicon, Wavendon Tower, Wavendon, Milton Keynesm

		Bucks. MK17 BLX, UK
MAROS	Simulation	Baker Jardine, Whitworth Building, Nat. Engin. Lab., East Kilbride,Glasgow G75 0QU, Scotland.
RAMP	Simulation	TA Consultancy Services Ltd., Newnhams',West Street, Farnham, Surrey, GU9 7EQ, UK.
PC-FOSP	Simulation	Sintef Safety and Reliability, N-7034 Trondheim, Norway.
RAMA	Analytic	DNV Technica, P.O. Box 300, N-1322 Hovik, Norway.

2.1. Ram Analysis Methods

The various reliability-availability methods can be broadly classified as measurement based and model based methods (Sathaye et al., 2000). Measurement based methods are expensive as they require building a real system or its prototype and taking measurements and then analyzing the data statistically, so its application is too limited. The model based methods have also two categories

(1) Monte Carlo Simulation

(2) Analytical Techniques

Both require a system model to be constructed in terms of random variables for the state of the underlying units (Dekker, 1996). Analytical techniques, on the other hand, use structural results from applied probability theory to make statements on various performance measures, such as the steady-state or the interval availability.

2.1.1 Simulation

It is too difficult (or sometimes impossible) to obtain reliability and availability measures analytically, for modern large and complex chemical plants with equipment that follows different failure and repair distributions. Simulation is used in these cases as an approximation to remedy the limitations of analytical methods. The simulation method uses a probability distribution function for equipment failure and repair actions and uses a simulation engine (usually a Monte Carlo simulation engine) to simulate the detailed dynamic behavior of the system and evaluate the required measures. The first step in the simulation method is to construct a system model (FTA, RBD, Markov state-space diagram etc.) describing the interrelations between underlying components. Equipment failures and maintenance actions are treated in the model as random discrete events for which the data is usually described in the form of probability distribution functions. Monte-Carlo simulation draws a realization of each random variable and then determines which units are down and for how long, from which the system availability over the interval of interest can be determined. By repeating this procedure an estimate of the system availability is obtained. In the last decade, a numbers of authors have published papers have on the successful application of simulation methods for availability analysis of industrial systems. Thangamani et al. (1995) assessed the availability of the fluid catalytic cracking unit (FCCU) of a refinery by using fault tree to model the system and Monte Carlo simulation to simulate the results. Recently, Cochran et al. (2001) have provide availability simulation results for the FCCU unit using Petri net and generic Markov chain models for the system analysis. Khan and Kabir (1995) reported the results of an availability simulation of an ammonia plant. They used a reliability block diagram to represent the system model. Cordier et al.(1997) used a stochastic Petri net to describe the interdependencies between various components of a gas terminal and performed the availability simulation using a Monte Carlo simulation engine. The major drawback of using a simulation method is that a lot of effort (time and cost)is required to perform the analysis and that there is always some degree of statistical error incurred.

2.1.2 Analytical Methods

Analytical methods are used to calculate the reliability and the availability measures of a system by using structural results from applied probability theory. A number of analytical methods have been developed which can be broadly categorized into "state space" or "non state space" modeling techniques (Sathaye et al., 2000). The choice of an appropriate modeling technique to describe the system behavior depends on factors such as

- Measures of interest (steady-state or time-dependent, reliability, availability etc.)
- Level of detail and complexity of the given system (size, structure etc.)
- Available tools to specify and solve the model
- Availability and the quality of data

The meaning of State is here "up", "degraded" and "down". A two-component system will have $2^3 = 8$ possible states.

2.1.3 Non-State Space Analytical Methods

Two prominent non-state modeling techniques used to evaluate system availability are the fault tree (FT) and reliability block diagrams (RBD).

Fault tree analysis (FTA) techniques, first developed in 1962 at Bell Telephone Laboratory, have long been used by a wide range of engineering disciplines as one of the primary methods of predicting system reliability and availability parameters. A fault tree is a pictorial representation of logical relationships between events and it can be used to represent a combination of events that will lead to system failure, called as top event. Several examples exist in the literature of the successful application of fault tree analysis to industrial process systems (Dhillon and Rayapati,1988).For example, fault tree analysis has frequently been used for reliability analysis of RO desalination plant (Hajeeh and Chaudhuri, 2000; Kutbi et al., 1981, 1982; Unione et al., 1980b).

A reliability block diagram (RBD) is a graphical representation of how the components of a system are connected reliability-wise. The simplest and most elementary configurations of an RBD are the series and parallel configurations. In a reliability block diagram each component of the system is represented as a block that is connected in series, and/or parallel, based on the operational dependency between the components. The reliability block diagram is by far the most popular modeling technique used in availability analysis of process systems. This can be explained by the fact that it is relatively easy to derive a high-level reliability block diagram from a process flow diagram. An availability study of an ammonia plant provides an example of the application of RBD for an industrial process system (Khan and Kabir, 1995).

2.1.4 State-Space Analytical Methods

The non-state models described above cannot easily handle more complex situations such as failure/repair dependencies, shared repair facilities, different types of maintenance for different units with different effects and different resource requirements. In such cases, more detailed models such as the Markov model and Petri net models can be used.

The Markov model provides a powerful modeling and analysis technique with strong applications in time-based reliability and availability analysis. The reliability/availability behavior of a system is represented using a state-transition diagram, which consists of a set of discrete states that the system can be in, and defines the speed at which transitions between these states take place. The transition from one state to the next state depends only on the current state irrespective of how the system has arrived in that state. The Markov models can be classified into continuous time Markov chain (CTMC) and Discrete Time Markov Chain (DTMC). The major disadvantage of Markov modeling is an explosion of the number of states even when dealing with relatively small systems. However, recently, Knegtering and Brombacher (2000) have proposed a new technique to reduce the number of Markov states by combining the practical benefits of a reliability block diagram. The published work (Kumar et al., 1991, 1996; Singh et al., 1990) on the availability analysis of a urea fertilizer plant provides an example of the application of Markov modeling in a process system design.

A **Petri net** is a directed-graph (digraph) consisting of places, transitions, arcs and tokens. Tokens are stored in places and moves from one place to another along arcs through transitions. A marking is an assignment of tokens to the places and these may change during the execution of a Petri net. If the transition firing times are stochastically timed, the Petri net is called a stochastic Petri net (SPN).If the transition firing is distributed exponentially, it is possible to make a statistical approximation of the same availabilities as those of homogeneous continuous Markov chains models. Winfrid G. Schneeweiss(2001) presented a tutorial of Petri net and it is shown how such Petri nets modeling, i.e., the construction of the relevant nets, works in practice.

2.2 Current Approaches to Implement Ram Tools

In last decade, a large number of research articles published enriched with implementing different techniques and methodologies in the field of reliability engineering. This review paper describes some of them briefly. Monica et al (2014) presented an application of Artificial Bees' Colony (ABC) algorithm to determine minimum cost configuration of complex repairable series-parallel system (butter oil processing plant industrial system) subject to given constraints on availability. This technique has been developed by Karaboga (2009) which is a population based approach and meta-heuristic technique. Lu and Wo (2014) used an analytical approach to evaluate the reliability of phased- mission systems (PMS) considering both combinatorial phase requirements (CPR) and repairable components. Cao et al(2013) used the discrete event simulation technique to estimate system costs (availability) and the Optimal Computing Budget Allocation (OCBA) mechanism to find the optimal maintenance policies for the system. Pardeep et al (2013) use Markov method to develop a Decision Support System for critical subsystem of a Beverage Plant. Kajal and Tewari (2012) applied Genetic Algorithm for Performance Optimization for Skim Milk Powder Unit of a Dairy Plant. Gupta and Tewari (2011) describe availability of a thermal power plant by simulation modeling. Sachdeva et al (2008) used Petri nets for Reliability analysis of pulping system. Bansal et al (2010) discussed the reliability factors using Boolean function technique in milk powder manufacturing plant. Schabe(1995) presented a method to obtain optimal replacement time of a complex system which is subject to maintenance. Based on the lifetime distribution function and the repair costs of the components they obtain the expected life cycle costs of the system. Gupta et al(1983) uses Boolean Function technique for reliability estimation of a complex system consisting of three subsystems A, B and C in parallel redundancy (1-out-of-3: G). Singh(1989) used Laplace transforms and generating function techniques to optimize a parallel redundant complex system having pre-emptive repeat repair in which the pre-empted unit of lower priority class joins the service only when all units of higher priority class in service or waiting have been served. The problem is solved with the use of Laplace transforms and generating function techniques. These subsystems are connected with six switching devices. Some alternative quantitative tools such as RBI (risk based inspection), RCM (reliability centered maintenance), and TPM (total productive maintenance) are frequently used in industry. Equipment maintenance policies follows two ways 1)

Corrective Maintenance (CM), which means repair when equipment fails, restoring it to normal function; and 2) Preventive Maintenance (PM), which is maintenance or replacement that occurs during normal functioning of the equipment in order to restore it to a better functioning condition and reduce the probability of equipment failure.

III. BARRIERS AND CHALLENGES OF RAM TOOLS IMPLEMENTATIONS

In spite of lot of different methods are available for reliability estimation and improvement, however Small and Medium Enterprises (SMEs) often encounter difficulties to implement RAM principles due to problems from both sides either Management or Engineering side. Here we presented some common challenges of implementing RAM tools as listed below-

3.1 Barriers from Engineering Side

- Inadequate knowledge or understanding of Reliability ineffective measurement techniques and lack of access to data and result.
- Difficulties to collect data from vendors
- Lack of up to date training and education
- Inappropriate condition for implementing reliability assessments
- Inadequate use of empowerment and teamwork
- Data collection is time consuming
- There is a lack of structured and quantitative approach to manage reliability, availability and maintenance measures throughout the life span of plants.
- The existing quantitative maintenance optimization methods are considered to be too complex and insufficient to handle practical real world conditions in industry.

3.2 Barriers from Management Side

- Lack of top management commitment
- Inability to change organization culture
- Improper planning
- Inability to build a learning organization that provides for continuous improvement
- Software tools, it often requires significant investments.

IV. CONCLUSIONS AND DIRECTION FOR FUTURE RESEARCH

In this review authors have gone through the number of research papers which contributed a lot to the field of reliability engineering over decades. After the significant review of literatures an attempt has been made by the authors to provide a direction for reliability engineers and industry leaders involved in RAM practice. Finally, we do see a wide scope for the newly developed methods, software's, techniques' and models such as, Artificial Bees' Colony (ABC) algorithm, Optimal Computing Budget Allocation (OCBA), Petri net, Markov models etc. The aforesaid tools will be useful to practically inclined reliability engineers because of its simplicity and feasibility. Finally, it is concluded that in future researchers should apply an optimal reliability tools by consideration of cost factor also to achieve the maximum reliability with minimum cost. Apart from cost, a need of structured and quantitative approach to manage reliability, availability and maintenance measures throughout the life span of systems. Engineering schools can play an instrumental role in developing a wide knowledge base in the field by including an introductory course on reliability engineering principles.

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