ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 1, Issue 3, July 2016

A Review on RAM (Reliability, Availability, and Maintainability) Analysis, its Applications and its Incorporation in the Modern World

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***Abstract*- This review paper focuses on the significance of RAM (Reliability, Availability, and Maintainability) analysis in all fields and it also tries to explain its existence in the modern world. The three factors reliability, availability, and maintainability together helps to manage a system effectively if all three are taken good care of separately and their combined effects and profits are evaluated with respect to system requirements, overall functioning and productivity in the long run. Therefore, RAM analysis is of great importance nowadays to effectively coordinate all the functions without any unexpected system failure. This paper also outlines the applications of RAM analysis being used in various fields and how it has been incorporated successfully in all these fields.**

***Index terms*- Existence, RAM analysis, System requirements, Unexpected system failure**

I. INTRODUCTION

RAM (Reliability, Availability, and Maintainability) analysis has become a root framework for the industries or for any organization. Those organizations which follow RAM analysis as their tool for solving problems, maintaining machinery and managing the system have more probability of survival in the market, as they can easily reduce the costs related to the repairs of machinery, new machinery or new component again and again. This helps them to focus on the processes, materials, tools, and new and better ways to increase the productivity of the entire system and consequently of the whole organization. Therefore, RAM analysis can be applied to activities/stages relating to both pre-production and post-production phase of any industry.

Reliability, availability, and maintainability (RAM) are the three factors which affect the whole organization in a number of ways. These three different terms possess different utilities and significance to a system. These also affect the life cycle costing to any system. RAM analysis can be used to predict the performance of a system. It can provide with a view to the engineers about the systems functioning capabilities, its flaws, and the subsystems which require more maintenance. It can also be used to identify about the functioning life cycle of equipment, type of maintenance to be performed, design the overall maintenance schedule, and creating an estimate about the total availability of the system. For all of this, it requires a complete failure data of system, subsystem, and its components. RAM analysis, in all, is a complete solution to increasing the life, maintainability, and performance of the system. Furthermore, sometimes it also uses other sets of reliability models, maintainability models, and other types of analysis such as FMEA (Failure Mode and Effect Analysis) and hazard analysis.

In this paper, a review has been done on various research papers of last ten years, focusing on using RAM analysis as their tool and incorporating it in research and technological advancements so as to solve a problem and improve the performance of a system. This paper identifies RAM as a useful tool to be applied in each and every analysis part of any organization or any industry. This paper aims to headline the useful aspects and applications of RAM analysis. It also shows that how it has been applied in any field, what were the tools used and in short, about the analysis part which has been done.

II. LITERATURE REVIEW (RAM ANALYSIS IN VARIOUS AREAS)

Hyon-Jong Lee *et al.* (2007) [1] applied applications of RAMS (Reliability, Availability, Maintainability, and Safety) analysis to the Korean railway industry of Maglev trains. The author had the aim that the Korean railway system should be regarded as one of the best systems in the world. For this, he compared the lifecycles of two different systems. First system was urban Maglev system and the other was the railway system according to the CENELEC EN 50126 standards. On comparison between the two systems, he also applied RAMS analysis on these systems. The author applied the procedures listed according to EN standards, initially to the rolling stock subsystem of the railway system, but the author proposed to also apply it for the whole railway system. He found out that the RAMS procedures were not applied to the railway systems and subsystems and also the RAMS budgets were not properly maintained for it. So, he devised a set of procedures or checkpoints for the engineers which are needed to be followed at each stage of the lifecycle to assure an acceptable level of safety standards.

K. Das *et al.* (2007) [2] used a mixed integer programming approach, multiobjective in nature, to maximize reliability and minimize costs for the design of a cellular manufacturing system (CMS). In the design of CMS, the main challenge was to select the process route for each part type which possess the highest reliability, and to minimize the total manufacturing cost, idle machines cost, and the material handling cost between different cells. The author described the approach which provides with a solution for flexible or alternative routing to cope with the failure conditions, thereby increasing the overall performance of CMS. They identified reliability as the main factor contributing to the overall performance of CMS. They aimed to come up with an optimized solution comprising both factors reliability and cost for an effective CMS. They suggested considering machine reliability while designing a cell in CMS. The approach also focuses on availability of machine to measure the machine functional capacity or performance so as to find the total availability of the system.

Herder *et al.* (2008) [3] have done their analysis on plastics industry. They developed a RAM model based on Reliability Block Diagram (RBD) which used a Monte Carlo simulation method. They identified that for an industrial scenario, RAM modeling is very important for validating a license, increased availability of the plant, and be up to date with the systems functional status. They identified that the company does not meet its productivity goals due to unexpected equipment failures. For that, they decided to apply the reliability engineering concept incorporating reliability engineering models along with the proper maintenance strategies. For solving the company’s problem, they built a quantitative RAM model from the old data of the plant. RAM simulation model developed by them helped them to realize the objectives such as inter-relation and dependency of components (in their functioning), identifying critical systems and subsystems, identifying role of redundant components and integrated buffers on the overall reliability of the system, and identification of availability data and proper allocation of resources. This analysis identified that which industries are feasible to apply RAM modeling and what are the requirements in industries for successfully applying RAM modeling. The analysis focused on minimizing the gap between the theoretical and practical application of RAM modeling in any industry. They concluded that the company got benefited from the reliability simulation modeling and the availability modeling. They identified that simulation modeling yields good results, but is labor intensive in nature and has a very short payback period. They realized that the availability simulation modeling is a very effective tool to be used in industries and it fits well into the Six-Sigma quality improvement processes. They also identified that the availability simulation modeling assists well in decision making and choosing the appropriate maintenance strategies for any plant. However, simulation modeling is labor intensive and time taking, but it can be managed well if industrial data are properly maintained and used for the analysis.

Rajiv Kumar Sharma and Sunand Kumar (2008) [4] applied RAM analysis to a process industry and used Markovian approach for modeling the behavior of the system. The analysis part included creating transition diagrams for subsystems, solving differential equations, and estimation of reliability and maintainability values after achieving a steady state solution. They identified that with the help of RAM analysis, the performance deciding factors such as system availability, Equipment Down Time (EDT) and Mean Time to Failure (MTTF) can be easily estimated. The above values help in understanding the system's RAM requirements. The objective of the analysis was to achieve effective system maintenance and effective operation. From the analysis, the subsystems exhibiting low reliability are found out and to achieve the overall reliability of the system to be high, preventive maintenance action should be taken for these subsystems. The authors concluded from the analysis that a proper maintenance schedule can be prepared for improving system effectiveness and suitable maintenance actions can be decided for the system/ subsystems.

Komal *et al.* (2009) [5] have used two techniques together 'Lambda-Tau methodology' and 'Genetic Algorithms' (GA) to form a new technique GABLT (Genetic Algorithms based Lambda-Tau) for their analysis. Reliability, availability, and maintainability of the system are calculated using Lambda-Tau methodology and GA was used to obtain the membership function. For carrying out further analysis, a general RAM index was used; and fault tree analysis was used for system modeling. They applied their approach to the press unit of a paper industry located in North India. They used GA to optimize the problem and to reduce the high uncertainties of the reliability indices which are in the form of fuzzy membership function. They identified that using this approach; RAM parameters can be calculated even if the data is limited and not precise. The objective of the analysis included analyzing the effect of failure types and patterns on different parameters of RAM. They used the analysis to analyze the system performance which would further lead in managerial advantages and could help in analyzing the role of cost with respect to the benefits obtained. They have concluded that through their technique, they were able to predict and model the system's behavior more appropriately and also they were able to choose the suitable maintenance actions to help minimize the maintenance and operation costs.

P.R. Thies *et al.* (2009) [6] carried out reliability analysis for wave energy converters and used Reliability Block Diagrams (RBD) as an approach for the analysis. They have stated that the analysis would yield results, if it is applied at the early stage of development. They applied the analysis at the early stage due to the lack of generic data.

Aijaz Shaikh and Adamantios Mettas (2010) [7] have applied RAM analysis to a natural-gas processing plant. They tried in their analysis to apply reliability simulation concepts practically into the complex industrial systems. To apply RAM analysis, they used the approach of Reliability Block Diagrams (RBD). They represented the inputs of the system as probability distributions and then to model the behavior of the system for various life cycles, they used the Monte Carlo simulation method. Monte Carlo simulation gave a statistical estimate of the system parameters like reliability and availability. They have done their analysis with the help of ReliaSoft Corporation's BlockSim software (version 7); and Reliability Phase Diagrams (RPD) were modeled into it. The objectives of the RAM analysis included:

(a) Prediction of production efficiency and availability.
(b) Identify possible causes for loss in production and availability.
(c) Performing cost analysis to find revenue loss due to unavailability.
(d) Identify the necessary actions to improve performance and thereby getting an estimate about the expected production and availability.

A.G. Mathew *et al.* (2011) [8] have conducted reliability analysis on the two identical units of the same plant, which was a continuous casting (CC) plant. Both units consisted of two identical 150 ton electrically operated overhead travelling (EOT) cranes operating at their full capacity and the failure in any crane could cause the unit to fully stop its processes. For analysis purpose, four years breakdown maintenance data was collected from a steel production plant and three types of failures were noticed in the system, which were replaceable, repairable, and reconditioning/reinstallation. From the data, the failure rates for different failure types and the repair rates and the probabilities for different types of failures were estimated. The analysis included calculating optimized reliability indices of system effectiveness numerically with the help of semi-Markov processes and regenerative point techniques. In case of failure, inspection was done to detect the type of failure and decide the suitable maintenance function. The real failure situations were incorporated into the model and analysis was done using actual estimated/calculated values of various probabilities and rates. The objective of the analysis was to do a real case study on CC plant so as to obtain various reliability indicators of system effectiveness.

Emmanuel Ohene Opare Jr. and Charles Park (2011) [9] have done their analysis for Next Generation Nuclear Plant (NGNP) project in order to achieve the goal of development and successful operation of the prototype of the fourth generation nuclear reactor. To reach the goal of high performance and availability, they constructed a RAM roadmap, to ensure various goals of system development and maturation also meet the availability requirements. Then, RAM simulation tool was used based on the RAM roadmap constructed for getting an estimate of the availability of the system when the system is operating on its current design configuration and maturity level. The analysis aimed to identify and track system vulnerabilities at the time of maturation and validation of system operational needs so as to satisfy the end user. RAM roadmap helped to track RAM improvement at the maturation level of the system. The RAM roadmap was constructed due to the complicated time-phased nature of the requirements. The NGNP project Technology Readiness Levels (TRLs) was also used in analysis for guidance and correlation of technical maturity with the required RAM activities. They were able to conclude that the analysis for the NGNP project was able to incorporate risk management techniques and tools for forecasting effective risk reduction, and verifying system operational requirements.

D.D. Adhikary *et al.* (2012) [10] have done RAM analysis on coal fired thermal power plants. The analysis was based on finding the RAM characteristics of unit-2 of a coal fired thermal power plant of 210 MW capacity. Through the analysis, they identified the critical subsystems on account of reliability, maintainability, and failure frequency so that necessary steps can be taken for increasing the availability of the plant. They compared the results so obtained with the unit-1 of the same power station. For performing the preventive maintenance, they also found out reliability-based preventive maintenance intervals (PMIs) at different reliability levels i.e., 75%, 80% and 90% of the subsystems. They sorted the failure and repair data for 10 subsystems; for easy estimation of reliability, availability, and maintainability. They observed that the subsystems considered for analysis were in series from the point of view of reliability and maintainability. They did not consider auxiliary mechanical systems which had no direct effect on the power generation for analysis. They found the time between failure (TBF) and time to repair (TTR) data for some subsystems to be independent and identically distributed whereas for some subsystems they found it to be contrary. They observed the subsystems which follow Weibull distribution and the subsystems following lognormal distribution, and accordingly they have drawn the conclusions for failure rate and the suitable maintenance actions.

Panagiotis Tsarouhas (2012) [11] has done RAM analysis on food industries namely, bread and bakery products; bottling and canning; and dairy products. The scope of the study was to review RAM analysis in the food industry so as to identify the critical points which need to be improved by increasing functional performance and maintenance

ISSN (Online) 2456-1290

International Journal of Engineering Research in Mechanical and Civil Engineering (IJERMCE)
Vol 1, Issue 3, July 2016

effectiveness. They concluded that the RAM analysis in the food industry helped to increase the performance and the rate of production in an industry. It also helped to analyze the effect of failures and helped in managing the operations related tasks. They identified that the reliability and hazard rate models are useful tools to analyze the current conditions and predicting reliability for improving the maintenance policies in food industries. As a result, this analysis proved beneficial for improving the decisions of the company as they could easily quantify profits and losses.

Zhaoguang Peng *et al.* (2013) [12] have done RAM analysis on a single satellite system using a probabilistic model approach. The analysis involved formal modeling of a single satellite and logical specification of RAM properties. They used a probabilistic model checker 'PRISM' to perform automated quantitative analysis of the RAM properties. Simulation had not been used for the verification of the satellite system due to consistently changing and complex design of the satellites. The formal modeling approach used was 'model checking' and the required RAM properties were expressed in temporal logic. The analysis part included applying probabilistic model checking, presentation of formal specification of a single satellite and its related continuous-time Markov chain (CTMC) model, and finally performing RAM analysis using 'PRISM'. They have concluded that the availability calculated was close compared to the actual data. They identified that many of the failures followed different distributions other than exponential distributions. Mainly, the failures of satellites followed Weibull distribution which also followed the bathtub curve.
Mohammad Javad Rahimdel *et al.* (2013) [13] have done reliability and maintainability analysis of pneumatic system of 4 rotary drilling machines in a copper mine. They have done reliability modeling of pneumatic system; and based on different reliability levels, they presented the maintenance scheduling. Based on the analysis, they have drawn the results and appropriate suggestions. They identified that time between failures (TBF) of machines B and C followed lognormal distribution and TBF of machines A and D followed the Weibull (3-parameter) and gamma generalized distributions.

H. Garg (2014)] [14] has done RAM analysis of an industrial system and used particle swarm optimization and fuzzy methodology as techniques for the analysis. The case study was based on a crankcase manufacturing plant. The objective of the analysis was to analyze the performance of an industrial system by using uncertain data. The analysis part included use of fuzzy set theory for managing uncertainties, generation of membership functions, and using particle swarm optimization to solve a non-linear optimization problem. He introduced a composite measure of reliability, availability, and maintainability (RAM) known as the 'RAM index'; to find the critical component of the system which was affecting the performance of the system. The RAM index governs the effects of failure and repair rate parameters on the performance of the system. Instead of constant rate models, he used the time-varying failure and repair rate parameters (following Weibull and normal distribution instead of exponential distribution) for the analysis. At last, he compared the calculated results with the existing methodologies. For measuring the performance of the system, he collected the data in the form of failure rate and repair time from the past records. The past records represented past system behavior filled with uncertainty. He used the fuzzy reliability approach because of the data uncertainty; which would otherwise yield uncertain results. He calculated the RAM parameters and their behavior; which was used for calculating the parameters in the form of fuzzy membership functions. Due to complex system, he optimized the range of reliability index for easy calculation, which would also help to focus on the most sensitive parts of the analysis. He used the Particle Swarm Optimization based Lambda-Tau (PSOBLT) technique to calculate the membership function of the reliability indices, by solving a non-linear optimization problem. He calculated the expression of the system parameters using Lambda-Tau methodology and generated their associated membership functions by formulating a non-linear programming problem and solving it with Particle Swarm Optimization (PSO) technique. In this way, he achieved the advantage of obtaining a small/ compressed search space for each calculated reliability index. He concluded that the results obtained have lesser range of uncertainties. He used a conceptual model to demonstrate how a suitable maintenance based on performance analysis can be identified. He identified the components of all the subsystems of the plant having maximum failure rates and arranged them in the order of preference of attention necessary for them.

Maciej Szkoda (2014) [15] has done comparative analysis of reliability of two types of rail gauge change systems, wagon bogie exchange and SUW 2000 self-adjusted wheel sets. The author has taken availability and maintainability analysis also into account. The objective of the analysis was to provide the methods to cope with the problem of different track gauges across different borders. This issue was of a great concern as the time spent in crossing the borders is about 46% of the total transportation time. The analysis was based on economic, legal and logistic aspects, and the associated benefits. The analysis was done with a motive to provide an efficient transportation mechanism for mainly transporting hazardous materials. The author concluded that the SUW 2000 system possessed high failure rate compared to the wagon bogie exchange system but has a higher technical availability ratio (A) and shorter Mean Accumulated Down Time (MADT) compared to the wagon bogie exchange system. With respect to maintenance point of view, the SUW 2000 system has shorter mean maintenance time (MMT) compared with the wagon bogie exchange system.

Panagiotis H. Tsarouhas and Ioannis S. Arvanitoyannis (2014) [16] have done reliability analysis at the entire line level and for all machines, for an automated yogurt production line of a dairy plant. The analysis part included performing trend and serial correlation tests to validate the assumption of the failure data being independent and identically distributed. They determined the theoretical distribution parameters that had the best fit to the failure data. Then, they developed the reliability, hazard rate, and the failure rate models for the entire production line. They concluded that the Weibull distribution was the best fit for the yogurt production line for describing the time between failures (TBFs). They identified the components whose reliability needed to be improved and required high maintenance action. They observed that failure rate of the production line was increasing which lead to the conclusion that the current maintenance strategy was insufficient and should be improved. They determined the components with the highest reliabilities. The reliability and failure rate models assisted in line operation forecasting.

Panagiotis H. Tsarouhas (2015) [17] has done reliability and maintainability analysis of repairable systems by taking polypropylene production (PP) industry as a case study. The polypropylene production (PP) line was an automated and repairable transfer line consisting of eight workstations in series. They have done reliability and maintainability analysis using statistical techniques on field failure data. The failure data was related to both time to failure and time to repair. The failure data collected for the PP production line and the associated analysis was valid for a period of 12 months. The methodology applied for the analysis had the objective to get an idea of the nature of failure patterns and about the reliability and maintainability characteristics in the form of precise and quantitative terms. The analysis identified the critical points, which required improvement by the use of effective maintenance strategies. The advantage that the used approach provided was the regular monitoring of the production process by appropriate indices. The analysis part included analyzing the reliability of repairable systems, gathering failure data for all workstations and the entire line, performing trend test and serial correlation test for failure data, and finally the reliability and maintainability analysis of PP production line. Through the analysis, the author found out the real operating time of the polypropylene production line. The author had drawn comparative results of reliability and maintainability for different workstations. The author found out that the time between failure (TBF) and time to repair (TTR) at line level followed the non-homogenous Poisson Process (NHPP) model, based on the power law process (PLP) with respect to the failure data. They concluded that the calculated reliability and maintainability for the entire production line and all the workstations would further in line operation forecasting. They also concluded that the analysis could be applied in the context of other chemical industries for improving the design and operation management of the production lines.

M.K. Loganathan and O.P. Gandhi (2015) [18] have done reliability analysis of CNC (Computer Numerical Control) camshaft grinding machine. The objective of the analysis was to develop an effective structural modeling approach for large manufacturing systems. They used structural graph models for the analysis which is a systems approach. The analysis part included developing structural graph models for reliability at various hierarchical levels, and obtaining the expression of system reliability by converting the reliability graphs into equivalent matrices. The matrices obtained helped in analyzing and evaluating the system. The reliability expressions obtained (for assembly, subsystem, and system level) at various hierarchical levels of the system helped in evaluating the reliability of the system and identifying critical elements with respect to reliability. They used structural modeling for calculation of reliability. To identify various structural elements and their interconnections, they developed schematic representations for each subsystem. They concluded that the approach used by them can be applied to other manufacturing systems (whether large or complex); and influence of other factors which affect system reliability can be also taken into account.

Mousa Mohammadi *et al.* (2016) [19] have calculated inherent availability of dragline machine and they have done reliability and maintainability analysis of dragline's subsystems in an open cast coal mine. They concluded from the RAM analysis that there were 2 major subsystems of the machine which were responsible for low inherent availability. They made suggestions to improve maintainability of one subsystem and the reliability of the other. They also concluded that the study of successive time to failures and RAM analysis can be used for strategies related to optimal replacement, procurement of spare parts and designing a preventive maintenance schedule.

A.K. Aggarwal *et al.* (2016) [20] have done reliability and availability analysis of a skim milk powder system of a dairy plant. They used the numerical method approach to calculate the long run availability and reliability, along with mean time between failures (MTBF). They used the approach for analyzing the effects of failure and repair rates of various subsystems on the reliability of the system. The numerical method approach was used instead of methods like Lagrange's method, Laplace transformation method, matrix method etc. since the system was complex and it also involved large number of differential equations. The skim milk powder system was a complex system and consisted of six repairable subsystems. The analysis was based on Markov birth-death process and it was assumed that the failure and repair rate of each subsystem follows exponential distribution. The analysis part included mathematical formulation of the system, generation of Chapman-Kolmogorov differential equations, and solving these differential equations using a numerical method known as Runge-Kutta fourth order method. They concluded that the analysis has helped in increasing the quality and production of skim milk powder. They identified the critical component, which showed the maximum effect on reliability and long run availability of the system. They concluded that the results of the analysis proved very beneficial for the evaluation of performance and availability of skim milk powder system and is also very helpful in deciding the best suitable maintenance strategies.

III. CONCLUSIONS

From all the description about the research work related to RAM analysis in the past 10 years, I concluded that this research paper can provide a brief and quick review of all the work done related to this field. It will prove useful for the researchers/practitioners/modelers/maintenance personnel to get an overview about the research, techniques used for analysis, and the field of application of RAM analysis which have not been tried yet. From this paper, I can hope that it will shape new paths for research and progress in this field.

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