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RELIABILITY ANALYSIS OF COMPLEX REPAIRABLE SYSTEMS: A ROADMAP

Sarfraz Ali Quadri

Dr. Dhananjay R Dolas

Abstract

The worst impact of the pandemic is visible on the industrial sector which was brought to almost shutdown; especially many Indian MSMEs are on the brink of closing down due to huge financial losses. We are now living in a post pandemic world where each small resource matters a lot and whatever we are producing must be very reliable to its intended applications. All the Industries especially MSME around the globe are facing a lot of challenges to achieve better productivity and customer satisfaction due to increasing necessity and demand for more reliable products at minimal cost. This has redefined the importance of reliability engineering and its impact on product/service lifecycles of complex systems and their economics. In the recent past Reliability centered assessments proved itself as one of the most trustworthy strategies not just to prolong the life of complex industrial systems by critical analysis of its repairable & non-repairable sub-systems but also by highlighting the most critical subsystems behind majority of failures. In this article, the aim is to provide a comprehensive state of art roadmap for reliability analysis of complex repairable system which will cover not only the theoretical aspects of Reliability analysis but will be focusing on various system structures and their respective effects of reliability analysis. Later part of the article will discuss a stepwise methodology for effective outcomes which will prove as a guide for practicing reliability and maintenance engineers and decision makers.

Keywords: Reliability, Weibull, Repairable System, MSME etc.

1. INTRODUCTION

The term 'Reliability' is very subjective in nature as the term itself was defined various times by various authors as per specific applications, the Merriam-Webster dictionary defines it as "The quality or state of being reliable" and in other literature it was defines as "the probability that a component or system will perform a required function for a given period of time when used under stated operating conditions" (Charles Ebeling, 1997). Reliability analysis has a redefined importance in today's world as we are surrounded by multiple complex systems right from our communication devices like mobile phone, laptop etc. to our transportation means like cars, trains and aeroplanes and we are hopelessly dependant on these complex systems to complete our work efficiently, productively and on time. If any of these systems fails to perform their work as expected, then it can have drastic effects on day to day functioning of our society. That's the reason these complex systems need to be as much reliable as possible. The manufacturers of all these devices and complex systems needs to pay keen attention the reliability of their parts right from the design stage, they need to understand the various critical sub-components involved in the assembly and their relative working with each other's, they need to pay attention to various failure modes associated with their product and the maintenance strategies for overcoming any unwanted breakdown or failures. The Original Equipment Manufacturers (OEMs) are very much aware about the impact of reliability studies in enriching their product cycles and they conduct dedicated reliability studies to predict and overcome any unwanted event. Here in this study the authors have put forth the aim of reviewing the available research and case studies of reliability analysis of complex repairable systems and to chalk out a stage-wise roadmap for any such reliability studies in the future.

2. LITERATURE REVIEW

Many international and national researchers have studied the aspects of Reliability, Product & System Reliability and Reliability centered maintenance individually as well as collectively for the various complex industrial systems. The Reliability approach is predominantly used for system analysis of a complex repairable industrial system and for planning their operational life and maintenance strategies. For the course of the current study we have covered different aspects of system analysis and the literature review of respective aspects are mentioned hereafter. The summary of literature is presented in Table no. 01.Javad Barabady [1] presents a case study describing reliability analysis of crushing plants in Jajarm bauxite mine. In this article reliability analysis has been done for various subsystem of the plant by using failures data. The parameters were estimated of multiple probability distributions, such as Weibull, Exponential, Lognormal distributions, have been estimated by using ReliaSoft's Weibull++ software. Results of the study show that the reliability of crushing plant 1 and crushing plant 2 declines after 10 hours to about 64% and 35% respectively. Javad Barabady & Uday Kumar [2] paper presents a case study of reliability and availability analysis of the crushing plant number 3 of a Bauxite Mine in Iran. For this research study, the plant was divided into 6 subsystems. The parameters of various probability distributions were estimated by using ReliaSoft's Weibull++6 software. The results of the research study highlight the critical components affecting are the conveyer subsystem and secondary screen subsystem and critical subsystems affecting availability are the secondary crusher subsystem and conveyer subsystem. The results also highlight that the reliability analysis is very useful for deciding maintenance strategies. Rezvanizaniani & et al. [3] focuses on field failure data collection and reliability analysis over a period in Raja Passenger Train Company of Iran. The results highlight that wheel sets are the most critical subsystem, and it utilizes the historical data of wheel sets to determine the reliability function. Vivek kumar & et al [4] focuses on examining & analyzing the failure times of boiler at thermal power plant to analyze its system reliability & critical failure expectancy. Reliability and maintainability analysis using Weibull probability plot & statistical analysis were presented as best suitable probability distribution. Masoud Naseri & et al [5] aims to broadly review and discuss different elements of Arctic offshore operating conditions specific to the Barents Sea, and further investigate various effects of such conditions on plant's Reliability, Availability & Maintainability. The research study presented fundamental information to academic and industrial sectors involved in the research and development of Arctic offshore O&G facilities and operations.

Table 1 Literature Review

Sr. No.	References	Industrial System	Approach/Methods Used	Software Tools used
[1]	Javad Barabady,(2005)	Crushing Plant of Bauxite Mine	Probability Distribution like Weibull, Exponential & Lognormal, Reliability Block Diagram	ReliaSoft's Weibull++6
[2]	Javad Barabady, Uday Kumar (2008)	Conveyor System of Bauxite Mine	Weibull Probability Plot, Probability density Function	ReliaSoft's Weibull++
[3]	S.M. Rezvanizaniani1, J. Barabady,Asghari1, And U. Kumar3 (2009)	Wheel Sets of Passenger Train	Failure Rate, Reliability Plot, Probability Density Function	Weibull++6
[4]	Vivek kumar, Saraswat (2021)	Boiler System of power plant	Anderson Darling test, Weibull Distribution using Least Square, Probability Density Function	MATLAB
[5]	Masoud Naseri, Javad Barabady (2016)	Offshore Oil & Gas Plant	RAM Approach, Probability Density Function	-
[6]	Dolas D.R., Jaybhaye M., Deshmukh S. (2014)	Diesel Engine of Compressor	Weibull Distribution, Weibull Probability Plotting,	Windchill quality solution 10.1 Tryout
[7]	Masoud Naseri, Javad Barabady (2016)	Oil & Gas Processing Plant	Expert based model, Weibull Analysis, Failure Tree	-
[8]	Ana Santose (2021)	Plastic extruder of a packaging Industry	Probability Density Function, Weibull Plot	Minitab
[9]	Anish Sachdeva, Dinesh Kumar, Pradeep Kumar (2008)	pulping system of a paper industry	Petri Nets Model, Root Cause Analysis, Reliability Plot	-
[10]	Simon Furuly, Javad Barabady, Abbas Barabadi (2014	Conveyor System on Coal Mine	Reliability Block Diagram, Weibull 3 parameter Distribution	ReliaSoft's Weibull++7
[11]	Jinghuan Ma, Yihai He, Chunhui Wu (2012)	Manufacturing Process	Process Reliability, Weibull Analysis, Least Square Method,	-
[12]	Bruno Zberg, Edward R. Arata, Peter J. (2009)	Mg-based metallic glass wires	Weibull Analysis	CAMSCAN
[13]	Milan Ambrozˇicˇ, Lovro Gorjan (2011)	Bending strength data for alumina test	Monte-Carlo simulations, Weibull 2 parameter Analysis, maximum-likelihood method	-
[14]	Dolas D.R., Jaybhaye M.D., Deshmukh S.D.,(2014)	Diesel Engine of Compressor	Age Replacement Model, Regression Model	MS Excel

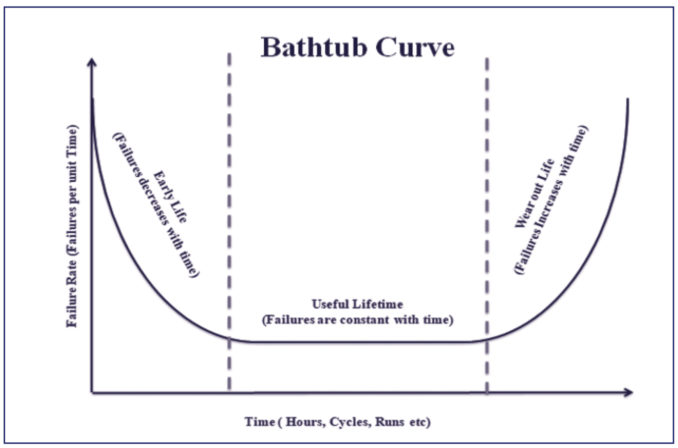
After reviewing various literatures from various researchers from across globe it was very evident that Weibull distribution is the most suitable probability distribution especially for complex mechanical repairable failures and systems. The success of the reliability is also very dependent on how well the system architecture is understood and the relationship between components is clearly defined reliability-wise. So further in this article we will focus more on system architecture and Weibull analysis and its parameters.

3. THEORETICAL ASPECTS OF RELIABILITY ANALYSIS

In industrial scenario "Reliability" is a continuously changing property but it is certainly one of the most desirable one for any machine, system or process. For an industry, reliability has critical implication of major amount of cost as well as safety and therefore it is very important to quantify the reliability of a complex repairable system. Reliability includes every aspect of a product's life, from its conception, design and development till its practical useful lifetime.

3.1 Bathtub Curve

Figure 1 Bathtub Curve of a product or process



The generalized bathtub curve for a product or proccess is shown in fihure 1, where the product life (Time) is on X-axis whereas Failure Rate is on Y-axis. The curve can be easily divided in 3 prominent phases i.e. Early life, Useful Lifetime and Wear out Life. In conception the product or process experiances infant stage failure and the failure rate decreases with time and reaches a more stable phase at the start of it useful lifetime where the failure rates are approxiamtely constant but there comes a phase where the lifecycle is mature enough and starts to show gradually higher failure rates with time i.e. Wear out life. In industrial system and products it is very critical to understant the right time of constant failure rate so that the customer does not face the infant failures. The reliability also plays a critical part in strategising the optimal cost plan to avoid higher failure rate of early and wear out phase.

All the important aspects of quantifying reliability like the reliability function, mean time function and failure rate function can easily be determined if we know the probability density function (pdf) and cumulative distribution function(cdf) of the system so let focus on the theoretical aspects first. The cumulative distribution function (cdf) is the probability of a random variable *'X'* to take a value less than or equal to *'X'*. Whereas the probability density functions (pdf) is the probability of a random variable *'X'* to take a value **exactly equal** to *'X'*. In reliability studies the *pdf* represents the relative frequency of failure times as a function of time whereas the *cdf* is the probability of failure before time which can be termed as "unreliability function". i.e. Q(t)

$$Q(t) = \int_0^t f(s)ds$$

Where 's' is a dummy integration variable,

Reliability and unreliability are always mutually exclusive so their sum is always equal to unity. Subtracting the unreliability function from 1 will give the "reliability function" i.e R(t) which is one of a most important functions in life data analysis. The reliability function is nothing but the probability of success in a given time duration.
Similarly, the reliability function for the exponential distribution

$$Q(t) + R(t) = 1$$
$$R(t) = 1 - Q(t)$$

$$R(t) = 1 - \int_0^t f(s)ds$$
$$R(t) = \int_0^\infty f(s)ds$$

where 'λ' is the sole parameter of distribution becomes
Similarly, the reliability function for the parameter Weibull distribution where 'β' is the shape parameter, *'η'* is scale parameter & *'γ'* is location parameter the distribution becomes;

$$R(t) = e^{-\lambda . t}$$

3.2 System Architecture for Reliability Studies

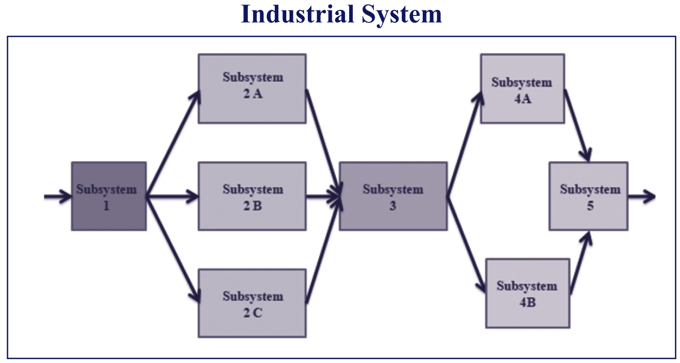
In reliability analysis one of the principal objectives is to obtain a life distribution that shows the times to-failure of a product, its

2-parameter Weibull: $R(t) = e^{-(\frac{t}{\eta})\beta}$

3-parameter Weibull: $R(t) = e^{-(\frac{t-\gamma}{\eta})\beta}$

subassemblies or a process. In reliability studies the researcher needs to be very focused on the components and subassemblies of a system and their relationship for getting desired functions because overall system reliability of an assembly depends on it. To understand these relationships usually a Reliability Block Diagram (RBD) are used which graphically showcases the relationships between components and how exactly they are connected in sense of reliability. For graphical representation a RBD of a complex Industrial system is shown in figure 3.

Figure 2. Reliability Block Diagram of a Complex Industrial System

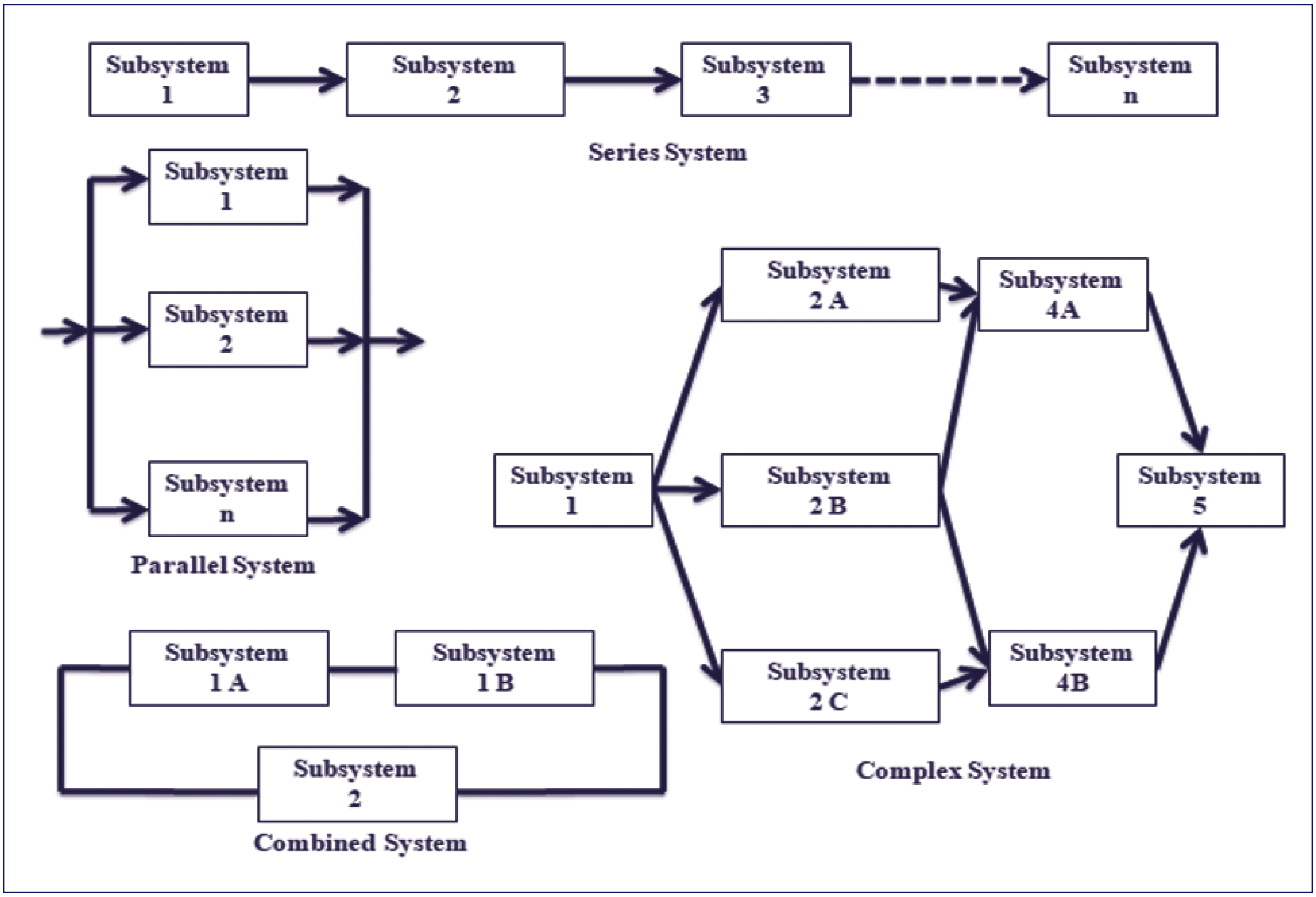


To construct a well-defined RBD the understanding of the reliability centered system architecture is very important and with that the well suited analysis method for that configuration is also critical. There are ‘n’ number of system configurations based on the complexity of the system so some of the very prominent configurations in repairable systems are listed and discussed for better understanding,

- Series configuration
- Simple parallel configuration
- Combined configuration
- Complex configuration
- k-out-of-n parallel configuration

These configurations are mainly dependency matrices for success of an operation, the simplest and most common “series configuration” are used in simple repairable systems where failure of any one component results in failure of the entire product or operation whereas in “parallel configuration” standby system are available in case of failure of one of the system. The graphical representation of some these configurations are shown in figure 4.

Figure 3 Various configurations of System Architecture as per reliability



4. LIFE DATA ANALYSIS USING WEIBULL ANALYSIS

Life data analysis is the method of critically examining a product’s life for failures. Although there are multiple analysis tools available for determining reliability characteristic and trends of population but Weibull analysis is one of the most suitable analysis technique when it comes to complex repairable systems. During literature review for this study we found out that in recent years Weibull analysis has proved itself most effective methodology and comparatively easier to implement by engineers and reliability practitioners. In Weibull analysis the *pdf* is used to determine the failure distribution and in most of the cases 3-parameter or 2-parameter Weibull is used where ‘β’ is the shape parameter, ‘*η*’ is scale parameter & ‘*γ*’ is location parameter. Basically the shape parameter ‘β’ helps to indicate the various types of failure over a lifetime of a product or service and ‘*η*’ shows the distribution of those failures.

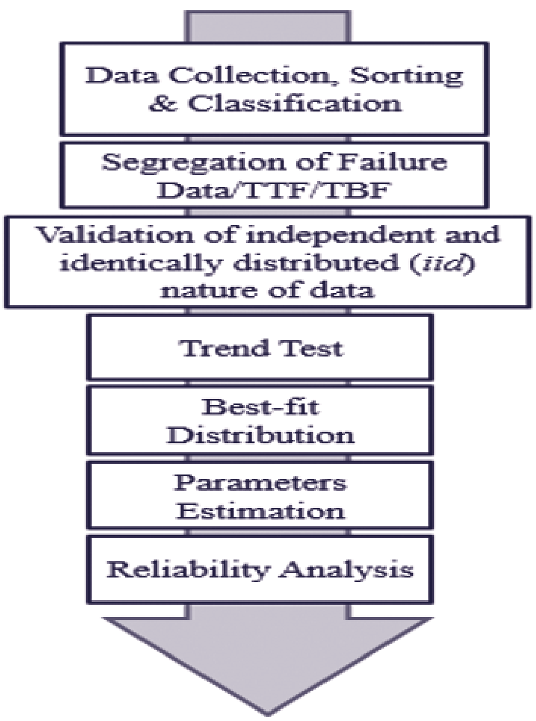
If ‘β<١’ it shows early life failures in a product life which means the failures are likely to decrease over time whereas ‘β>١’shows wear or lack of maintenance which means the failures are likely to increase over time. In useful work life of product when the failure rates are constant usually ‘β=١’

If ‘*η*’ is increased by keeping ‘β’ same, the failure distributions get stretched decreasing the height of curve and If ‘*η*’ is decreased by keeping ‘β’ same, the failure distributions get pushed in increasing the height of curve as it has the same units as Time.

5. ROADMAP FOR RELIABILITY ANALYSIS OF A REPAIRABLE SYSTEM

The Reliability analysis always starts from first step of proper and well planned data collection usually failure data, Time to Failure (*TTF*) or Time before Failure (*TBF*) in case of repairable systems. The entire analysis is dependent on the most basic assumption that the collected data is independent and identically distributed (*iid*) in time so the second stage is to validate the *iid* nature of data for the system otherwise improper conclusion can be drawn which won't fully interpret the system under study. If the *iid* validation is confirmed, then and then only probability distribution can be implemented. The simplest way to validate the *iid* is a graphical trend test followed by fitting the TBF with a probability distribution. Finally, the parameter estimation of probability distribution can be carried out with a best-fit distribution using various available software tools. If the *iid* validation is not confirmed, then the statistical reliability analysis techniques may not be suitable. The graphical representation of the roadmap for Reliability analysis of a repairable system is shown in Figure 7.

Figure 4 Roadmap for Reliability analysis of a repairable system



SUMMARY

The research study showcases aspects of performance analysis of complex repairable systems using reliability approach. It provides a comprehensive literature review of various researcher work covering various complex repairable system. It highlights that Weibull distribution is most suited for modeling mechanical failures. The study also provides a stepwise roadmap for reliability practitioners to analyze reliability of complex industrial systems.

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AUTHORS

Sarfraz Ali Quadri, Research Scholar, Mechanical Engineering Department, Jawaharlal Nehru Engineering College, (JNEC), MGM University, MGM Campus, N-6, CIDCO, Aurangabad – 431 003, (MS) Aurangabad
Email: sarfrazali.research@gmail.com

Dr. Dhananjay R Dolas, Associate Professor, Mechanical Engineering Department, Jawaharlal Nehru Engineering College, (JNEC), MGM University, MGM Campus, N-6, CIDCO, Aurangabad – 431 003, (MS) Aurangabad
Email: drdolasjnec@gmail.com