EVALUATION OF RELIABILITY, AVAILABILITY AND MAINTAINABILITY OF A PRINTING PRESS

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR THE DEGREE OF

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PRINTING ENGINEERING AND GRAPHIC COMMUNICATION

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Certificate of Recommendation

This is to certify that **AVIJIT KAR** (Class Roll No. – 001711602007, Examination Roll No – M4PRI19002, Registration No. - 140962 of 2017-2018) has completed his dissertation entitled, "**EVALUATION OF RELIABILITY, AVAILABILITY AND MAINTAINABILITY OF A PRINTING PRESS**" under the supervision and guidance of Dr. Arun Kiran Pal, Professor, Department of Printing Engineering, Jadavpur University, Kolkata. We are satisfied with his work which is being presented for the partial fulfilment of the degree of Master of Technology in Printing Engineering and Graphic Communication, Jadavpur University, Kolkata.

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The thesis at instance is hereby approved as a creditable study of an Engineering subject carried out and presented in a manner satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve this thesis for the purpose for which it is submitted.

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Declaration of Originality and Compliance of Academic Ethics

I, **Avijit Kar,** hereby declare that this thesis entitled "Evaluation of Reliability, Availability and Maintainability of a Printing Press", contains literature survey and original literature survey and original research work carried out by myself, as a part of my Degree of Master of Technology in Printing Engineering and Graphic Communication in the Department of Printing Engineering.

All the information in this document have been obtained and presented in accordance with academic rules and ethical conduct.

I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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CONTENT

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Abstract

The unexpected failures, downtime associated with breakdown & make ready, loss of production and higher maintenance costs are the major problem in any printing press. Evaluation of reliability, availability and maintainability strategy helps in designing an alternative strategy to minimise the risk by identifying the breakdown pattern and then increasing the reliability. Reliability analysis is necessary for every types of machinery for fault detection, risk assessment and evaluation, maintenance planning. Technical audit is performed in this study to understand the overall performance scenario of the press. Performance of the printing press depends on reliability and availability of the machineries used, working environment, maintenance, operating process and specialized skill operators etc. The aim of the proposed study is to analyse reliability and availability for maintenance planning on the basis of risk index and overall equipment effectiveness. It helps to identify the root causes of failures of critical machine on the basis of level of risk and preselected acceptable level of risk. And maintenance of equipment is prioritized based on the risk which helps in reducing the overall risk of the press.

The case study of the printing press is used to illustrate the strategy. Result indicates that the strategy is greatly helpful for deciding the maintenance intervals, planning and organising maintenance of the components of printing plant by reducing the risk due to failures. And it will help to increase the reliability of the printing press, reduce the cost of maintenance including the cost of failures. Therefore the outcomes demonstrate the availability and reliability significance measures can be utilized as a rule for organizing the efforts for reliability and availability improvement of the printing press.

Keywords: Reliability, availability, maintainability, risk index, overall equipment effectiveness.

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Reliability-Availability-Maintainability: RAM

Risk Based Maintenance: RBM

Total Productive Maintenance: TPM

Mean time to repair (MTTR): $\frac{1}{\mu}$

Mean time between failures (MTBF): ξ

Standard deviation of MTBF: σ

Mean downtime: MDT

Mean active maintenance downtime: MTBM

Risk index: RI

Overall equipment effectiveness: OEE

Mean operating time: t

Shape factor: β

Scale factor: Ƞ

Location parameter: γ

Correlation coefficient: $R_{x,f(x)}$

Anderson-Darling: AD

Downtime: DT

Production loss in impression per time: PL

Selling price in rupees per impression: SL

Maintenance cost: MC

Production loss cost: PLC

Fault-Tree analysis: FTA

Time-Motion study: TMS

Impression per hour: i.p.h.

Chapter 1

INTRODUCTION

1.1 Introduction

Plant's machine and equipment will not remain safe or reliable if it is not maintained properly. General objective of the maintenance process of a machine is to achieve the possible safety with the lowest possible cost from the failures or unwanted breakdowns. In the present study the concept of reliability-availability-maintainability (RAM) and risk based maintenance (RBM) strategy has been adopted to inspect the high risk and then attempts have been made to minimize the actual failure rate with a logical approach. For this data of different components of printing plant have been gathered and well analysed so that tolerable risk criteria can be achieved.

The unexpected failures, the downtime associated with such failures, the production loss and the higher maintenance cost are major problems of any printing press. RBM helps to minimise this risk resulting from breakdown or failures.

The present study deals with the determination of reliability and availability aspects of one of the significant constituent in a printing press. In order to evaluate the availability performance of the components, intensive studies have been carried out to collect accurate information for availability analysis. The reliability analysis is also performed using the Weibull distribution & the various data plots as well as failure rate information help in achieving results that may be utilized by the printing press for reducing unexpected breakdowns and will enhance the reliability & availability of a printing press.

1.2 Background of the study

The reliability of an item is the probability that the item will perform a specific function under specified operational & environmental conditions throughout a specified time. Reliability must have certain criteria and depend on various factors most which are random. It is difficult to measure reliability since there is no instrument by means of which these may be done for particular equipment.

In the present work maintenance is done on the basis of risk index which is measured by the level of risk & acceptable level of risk. Machine or equipment in critical conditions can be identified based on these levels. Now a days there are many printing plants in India. They have faced a lot of problem regarding the maintenance of machineries and its sudden failures. Maintenance of printing machine is prioritized based on the risk factor which helps to reduce the overall risk of the printing plant.

1.3 Salient feature of the existing press

The present study is conducted at Ganashakti Printers Pvt. Ltd. situated in Kolkata, India. Ganshakti Patrika is an Indian Bengali daily newspaper published from Kolkata, India. Daily newspaper along with different kinds of jobs like supplementary parts of newspaper, books, brochure, magazines etc. are printed in this press. It has pre-press section, press section where main printing is done and post press section where output of printing section is packed to deliver. Pre-press section comprises of two components (CTP1 & CTP2) and one subcomponent (exposure unit) and press section consists of one component (main printing machine) and two subcomponent namely Compressor-1 and Compressor-2. But only Cmpressor-1 had been taken into consideration for the study as the second compressor is used for emergency backup purpose.

1.3.1 Present scenario

Maintenance is the most important part of a printing press. The machines are running almost many years and consequently availability and reliability checking is found to be a most important part of the printing press. In a printing press if any component or subcomponent has got breakdowns the operational process would be subjected to some troubles.

The printing press currently has one four colour printing web-fed offset machine, two CTP units, one plate exposure unit and compressors. The details of different components of the printing press are summarized below in Table 1.1.

Table 1.1: Different components of the Press

Sl. no.	Name of machine	Name of the company	Year of manufacture	Capacity (Impression / hr.)	Component or Subcomponent	Output
1.	Printing machine	Orient Xcell, 3c-1	2009	41200 (approx.)	Component 1 (C1)	Daily newspaper, supplement, book, magazine etc.
2.	Computer to plate 1	Epson	2014	20 (approx.)	Component 2 (C2)	Preparation of plate for printing
3.	Computer to plate 2	Epson	2009	15 (approx.)	Component 3 (C3)	Preparation of plate for printing

4.	Exposure unit	Technova, Proteck, Ecolux-i	2005	30 (approx.)	Sub-component 1 (SC1) of C2 & C3	Preparation of plate for printing
5.	Compressor	-	2009	-	Sub-component 2 (SC2) of C1	-

Printing press expends 40-45% of total money on maintenance. It is now necessary that the expenditure for the maintenance purpose can be reduced more affectively. To check out these possibilities the present investigation has been undertaken.

1.4 Aim of the present study

The study deals with the preparation of Reliability-Availability-Maintainability (RAM) analysis along with Risk Based Maintenance (RBM) strategy and Technical Audit of a printing press in order to minimize any unexpected production loss due to various component's downtime. The present study is conducted on the basis of regular visits to the printing press continuously for three months in order to get potential data. These data are processed and then analysed in order to get suitable results. So the main objective or aim of the present study as follows:

1. To collect the data of failure scenario of each system.
2. To determine the Probability of system failure.
3. To analyse the Consequence of failure from maintenance cost and production loss cost of each and every component.
4. To find out the risk from consequence and failure probability.
5. To prepare threshold level risk and to compare the level of risk with this threshold risk level and also determine the risk index,
6. To check whether the risk index is acceptable or not and provide necessary suggestions for maintenance strategy and planning.
7. To check the reliability from failure analysis.
8. To check the availability of the press.
9. To discuss the maintenance planning and maintainability.
10. To check whether the implementation of Total Productive Maintenance is reasonable or not.

1.5 Scope of the study

The scope of the present study is to obtain maintenance policies which optimize the production rate by minimizing machine downtime. When a machine is likely to breakdown, necessary steps will take to check this. The RAM analysis discussed in this study has following aspects:

1. Breakdown analysis of the printing press involving various types of failures and total no of failures on a certain period of time.
2. FTA analysis.
3. Evaluation of reliability and probability of failure of different component of the printing press.
4. Availability analysis of the printing press.
5. Evaluation of risk index of different components.
6. Development of maintenance approach for risk reduction.
7. Identification of root causes of failure of all components by analysing the actual causes and their effects on the basis of Fish-Bone Diagram through brainstorming.

Chapter 2

Literature Survey

2.1 Introduction

It is obvious that many techno-specialist, research personal, statistical experts observe that several strategies like Risk Based Maintenance (RBM), Total Quality Management (TQM), Reliability Availability & Maintainability (RAM), Total Productive Maintenance (TPM) etc. should be implemented to determine failure rate. After finding the root-cause of failures and its corresponding risks or risk-factors, those strategies or techniques are implemented for the betterment of existing plant or system or machine.

It has been attempted here to bring the important works together related with RBM strategy and Technical Audit. RBM strategy has already been applied in different sector of industries like gas pipelines, medical sectors, gas turbine power system, steel plant, fuzzy analytic network process, nuclear plants, soft drink bottling plant etc. But now there is a very few application of RBM strategy in printing press. So the RAM and TPM strategy of printing press is presented in this study.

2.2 Review of Previous Investigations

In this study, an attempt has been made to bring the important works in this field together has found in literature till date. Again unfortunately many of the publications are not easily accessible. For ready reference & convenience it is intended to make a brief survey on the important relevant works published mainly after 1990.

The present investigations are subdivided into three sections.

2.2.1 Review on Risk Based Maintenance (RBM) strategies

The theory behind RBM methodology started from 19th century. Chen & Toyoda (1990)[1] proposed a strategy for maintenance scheduling based on equalising the incremental risk. The risk based inspection & maintenance strategy developed by American Society of Mechanical Engineers (ASME) (1991) [2] was used as a basis for developing a document on “Risk based inspection” by American Petroleum Institute, API (1995) [3]. Work by Aller, Horowitz, Reynolds, Weber & Renolds (1995) [4] constituted the basis for development of risk based inspection policy for equipment owned by Brunei Shell Petroleum {Hagemeijer & Kerkveld (1998)} [5].

T. J. Christ, et. al (1997) [6] described that the steam turbine risk assessment project was initiated to develop a methodology to address the issue of optimization of overhauls by identifying and quantifying the risk associated with maintenance, operation, and engineering. Furthermore, this risk is related to the economic impact of the decision. The methodology followed was an adaptation of ASME Risk Based Inspection Guidelines. Jerry H. Phillips, PE (October 1, 1997) [7] mentioned that Maintenance techniques and resources was focused on those components that have the highest risk-significance. The techniques have been developed and applied at a number of pilot plants. Risk-based approaches are based on maintenance activities of components where failures can occur and plants have high consequences. Results obtained indicate that safety can be increased and inspection of piping components can be decreased. These techniques have been developed by teams working with the ASME Centre for Research and Technology Development.

A risk based approach has been applied successfully to the maintenance of oil pipelines. K.P. Dey, S. O. Ogunlana, S. S. Gupta & M. T. Tabucanon (1998) [8] discussed a simple risk based model for the maintenance of a cross-country pipeline. Nessim & Stephens (1998) [9] proposed a quantitative risk analysis model and P. M. Dey (2001) [10] described a general model for inspection & maintenance of cross-country pipelines. The use of a risk based policy in the maintenance of medical devices has been studied by M. Capnano & S. Koritko (1996) [11] and Ridgway (2001) [12]. Later, Redmill (2002) [13] focused on risk analysis steps process (identification, analysis & assessment). Khan & Haddara (2003) [14] described the method for maintenance planning improvement based on Risk based maintenance & developed three modules viz. risk estimation, risk evaluation and maintenance planning module and later it has been extended by L. Krihnasamy, et. al. (2005) [15] where they showed other case studies and the method was adapted to other domain. M.J., et al, (2003) [16] stated the use of a non-destructive acoustic evaluation technique as a Risk Based Inspection tool to detect the corrosion of steel reinforcement in concrete. It offers the potential to save time and money for facilities, owners and users.

Rebecka Thorwaldsdotter (August 2006) [17] described the overall purpose of Quantitative Microbial Risk Assessment (QMRA) and explained if and how QMRA can be used as a basis for an Hazard Analysis & Critical Control Point (HACCP analysis in water treatment industry. Nan Kjellberg & C. Sandstorm (August 2006) [18] had studied that how environmental risks should be incorporated into the municipal management in Sweden and to evaluate the potential use of the program associated with reduced accidents with the help of Riskera. Riskera is a tool based on Geographic Information System (GIS), which has been developed by the Swedish Rescue Services Agency (SRSA). Nils Rosengren (August 2006) [19] in his project implemented risk management within the City Tunnel Project. Furthermore, this work described the proposal for organizational risk management. The model is based on the organization’s current management systems and presents a solution for the implementation of risk management in the project.

E. Michalopoulos, et. al. (2008) [20] in his paper present a generalized method for management decision making incorporating risk assessment techniques. The risk based decision making methodology had been applied to European Union expenditure programs to implement its regional policy, such as the community support framework, community initiatives, special initiatives and other European policies. J. T. Fong, et. al (2010) [21] derived risk-uncertainty formula by computing separately the probability-uncertainty and the consequence-uncertainty of a given failure event, and then using the classical theory of error propagation they computed the risk-uncertainty within the domain of validity of that theory. In 2013, Liu Deke [22] described the application of risk based inspection (RBI), reliability centred maintenance (RCM) and risk based maintenance (RBM) in the China Oilfield Service Limited (COSL). He also studied the application of risk approach in maintenance management during the life cycle of facilities to reduce risk, improve reliability and save cost. Leistad & Braddley (2009) [23], Meyer & Renners (2013) [24] and J. E. Vinnem (2014) [25] presented & discussed different aspects of risk management related to the offshore oil gas installation and also applied several standardised operational risk assessment including a system for work permits & Safe Job Analysis (SJA).

Terje Aven & Bodil S. Krohn (2014) [26] described that the new perspective on how to understand, assess and manage risk. The main aim of this paper was to present a new way of thinking and which provides new insights as well as practical guidelines for the concept of mindfulness as interpreted in the studies of High Reliability Organisation (HRO). Florin Boghean (2015) [27] intended to implement of the risk management system through relevant international standards. Sanja Mandic (2015) [28] presented the ways of risk measuring and analysis, in order to make best decisions considering supply chain, as well as risk responding strategies. Abdul Hameed (2016) [29] in his research, derived a risk-based shutdown inspection and maintenance interval optimization technique for a processing facility. It had been attempted to optimize individual equipment inspection and maintenance interval considering cost, risk, availability and reliability. For an effective inspection and maintenance strategy, the stochastic nature of failure has to be taken into consideration by Hameed. The proposed methodology aims to minimize the risk of exposure considering effect of failure on human life, financial investment and environment by optimizing the interval of process unit shutdown.

In 2017, Daranee Pimchangthong and Veera Boonjing [30] implemented various risk management practices influencing the success of IT projects. Data were collected from 200 project managers, IT managers, and IT analysts in the IT firms through questionnaires and analysed using the Independent Sample t-test, One-way ANOVA, and Multiple Linear Regression. Recently, Evangelos Michalopoulos [31], completed his Doctoral Thesis on "Risk based decision for the Management of European Operational Programs" in June, 2017. In the thesis he focused on the combined risk-benefit-cost assessment for both physical & procedural systems in risk assessment & cost management of European Regional Operational Programs by implementing a tool called RBM which may help to address and measure the European Commission's efforts for anti-fraud measures & assessments. This study also covers the analytical studies of frequencies, risk, consequences, benefits & cost quantity.

2.2.2 Review on Technical Audit

To the best of the knowledge of author, publications on technical audit are not so much available. Only a few are cited here which are available on open literature.

Emma Jarun & Sara Radu (2006) [32] reported a study to identify and categorize suitable audit users and furthermore establish which values these users experience. The aim of his report has been fulfilled by analysing the interviews carried out with several companies using audits as a part of their risk management process.

In March 2012, S. B. Srivastava [33] has emphasised Quality and Profitability Improvement by Technical Audit of a process plant. He also concluded that the Technical Audit will increase the Customer and Owner's DELIGHT and gives a NEW thrust to the organization. He also implemented different methods like Fish Bone Mechanism, Pareto Mechanisms etc. The Technical Audit assures the increased knowledge about the Product Quality and Profitability. And further he suggested few remedial measures

Milan Delic, et. al.(2015) [34] furnished an attractive model for management system auditing based on risk assessment. In his paper, he adopted a model which refers to the risks concerning the achievement of audit goals, along with risks of the audit to interfere with audited activities and processes of the organization. Moreover, the proposed model is simple for application and is based on assessment of two crucial components of risk, namely, the likelihood of occurrence and the significance of consequence.

2.2.3 Review on Reliability-Availability-Maintainability (RAM), Total Productive Maintenance (TPM) and Overall Equipment Effectiveness (OEE)

F. Herbaty (1990) [35] mentioned in his article that Condition Based Maintenance (CBM) is based on the same principle as preventive maintenance although it employs a different criterion for determining the need for specific maintenance activities. Hassett (1995) [36] proposed a method which combines time varying failure rates and Markov chain analysis to obtain hybrid reliability and availability analysis. However, combining these techniques were dependent on the size of the system. In 1997, A.K. Munns, et. al. [37] stated that optimal time to perform maintenance is determined from actual monitoring of the asset, its subcomponent, or part. The assessment varies from simple visual inspections to elaborated automated inspections using variety of condition monitoring tools and techniques. S. Schimidt (1997) [38] concluded in his findings that the main TPM improvement activities depends on the appropriate implementation of Change-Over-Reduction-Engineering (CORE) methodology in order to achieve maximize equipment effectiveness, eliminate all the six big equipment-related losses.

McKone E. Kathleen & Schroeder G Roger (1998) [39] proposed a plan of Structural Equation Modelling (SEM) by relating Total Preventive Maintenance (TPM) and manufacturing performance to share a positive and vital relationship with low cost and high levels of quality & productivity. Further, Just-In-Time (JIT) practice was incorporated to derive a significant bond between TPM and manufacturing performance. O. Ljungberg, et al. (1998) [40] determined various types of manufacturing losses, in order to command activities and allocate resources in an optimal way. He also stated that if the production process is new to the firm the Overall Equipment Effectiveness will be less than if the firm is habituated to the manufacturing layout. Q. Michelsen (1998) [41] assessed the reliability analysis as a useful tool for determination of risk and the design of safety system. P. Jonsson & M. Lesshammar (1999) [42] proposed a technique where it is focused on four critical dimensions (what to measure) and two characteristics (how to measure) of a total production measurement process. F. Ireland & B.G. Dale (2001) [43] focused on TPM implementation in three companies where financial disturbances were present. Senior management in each of these companies had taken the initiative for TPM implementation by setting up appropriate organisational structures. Nakajima's seven steps of autonomous maintenance was taken into due consideration [43]. Several other TPM pillars were set up which included education and training, quality improvements, quality maintenance and safety.

J. Woodhouse [44] (2001) stated in his research paper that Reliability Centred Maintenance (RCM) gives some logical rules for determining what type of maintenance is appropriate, based on failure mechanisms and consequences and is suited to complex plant where there are lots of failure modes. A.K. Vermar, et. al. (2002) [45] observed that there was a lack of defined approach for implementation of RCM as a maintenance methodology due to some difficulty. Thomas R. Pomorski (2004) [46] examined the basic concepts of TPM and reviewed the significant literature related to design, implementation and maintenance of TPM programmes in manufacturing processes. His comprehensive study included the organizational structures, human interactions, analytical tools and success criteria associated with the enforcement of Total Productive Maintenance process. J. August (2004) [47] reported that the primary concern for industrial organizations adopting RCM is without excessive costs or not. August, Ramey & Vasudevan (2005) [48] reported an extreme case of the RCM analysis of Nuclear Plant.

P. S. Rajpal, et. al. (2006) [49] proposed many factors that affect the Reliability, Availability and Maintainability (RAM) of a complex repairable system. These factors include conditions of machinery (type, number of machines, age, arrangement of machines relative to each other, arrangement of components in the machine, inherent defects in components), operating conditions (level of skill and number of operating personnel, working habits, inter personnel relationships, absenteeism, safety measures, environmental conditions, severity of task assigned, shock loading), maintenance conditions (competence and strength personnel, attendance, working habits, safety measures, inter-personnel relationships, defects introduced by previous maintenance actions, effectiveness of maintenance planning and control) and infrastructural facilities.

Faisal Khan & his co-author (2008) [50] presented in their paper that a risk-based methodology to estimate optimal inspection and maintenance intervals which maximize a system's availability. The methodology was comprised of the following steps: availability modelling and risk-based inspection and maintenance calculations. The proposed methodology was applied to the steam generating system of an oil fired thermal power plant. The authors presented a case study which involved the application of the method to a steam generating unit in a power plant. The unit under consideration was further subdivided into ten subsystems. These subsystems are simulated using the proposed approach to achieve a target availability of 99.9%. Ying Shen Juang, et. al. (2008) [51] proposed a genetic algorithm based on optimization model to improve the design efficiency. He also developed a knowledge-based interactive decision support system to assist the designers set up and to store component parameters during the intact design process of repairable series-parallel system. Rajiv Kumar Sharma and Sunand Kumar (2008) [52] presented the application of RAM analysis in a process industry where Markovian approach is used to model the system behaviour. For carrying out analysis, transition diagrams for various subsystems were drawn and the corresponding governing differential equations associated with them were formulated. After obtaining the steady state solution the corresponding values of reliability and maintainability were estimated at different mission times to increase performance. B. A. Ellis (2008) [53] stated that the objective of Condition Based Maintenance (CBM) was to minimize the total cost of inspection and repairs by collecting and interpreting intermittent or continuous data related to the operating condition of critical components of an asset. I.P.S. Ahuja & J.S. Khamba (2008) [54] proposed a paper on the open literature of Total Productive Maintenance (TPM) and enlightened an overview of the TPM processes practiced by different manufacturing firms. They further focused on the eliminating the barriers in TPM Implementation.

N.S. Mahesh, et. al. (2009) [55] performed a case study on Overall Equipment Effectiveness improvement by TPM and 5-S's techniques in a CNC machine shop. They aimed at minimizing breakdowns, increasing performance and machine quality rate to improve effectiveness. S. Gupta, et. al. (2009) [56] assessed the reliability and availability of a critical ash handling unit of a steam thermal power plant by making a performance analysis and modelling, using probability theory and the Markov Birth-Death process. After that, steady state probabilities were determined. Certain decision matrices were also developed, which provide various availability levels. The behaviour analysis of the reliability module revealed that the availability decreases with increasing failure rates, while operational availability improves with initial increases in repair rates for different subsystems. Sanjeev Kumar, et. al. (2009) [57] discussed the performance evaluation and availability analysis of ammonia synthesis unit of a fertilizer plant. For the evaluation of performance and analysis of availability, a performance evaluating model had been developed with the help of mathematical formulation based on Markov Birth-Death process using probabilistic approach.

R. Khanduja, et. al. (2010) [58] dealt with the mathematical modelling and performance optimization for the paper manufacturing system in a paper plant. The paper making system had been divided into four main subsystems, arranged in series and parallel. The mathematical formulation of the problem was done using probabilistic approach and differential equations are developed based on Markov birth-death process. These equations were then solved using normalizing conditions to determine the steady state availability of the paper making system. S. Fore & L. Zuze (2010) [59] proposed a plan for improvement of Overall Equipment Effectiveness through Total Productive Maintenance. They approached a case study where focus was given on improving the maintenance in a manufacturing setup.

They used different data collection methods like interviews, reviewing, documenting, and historical records in addition to direct and participatory observation. They suggested a number of recommendations like full employee participation, trained personnel to meet the present and future trends of manufacturing criteria, keeping a track record of all corrective maintenance jobs and preventive maintenance inspections. But they further stated that for large plants, these are impossible to handle manually. So they recommended the implementation of Computerised Maintenance Management System (CMMS). Manish Kumar Goel, et. al. (2010) [60] worked in the field of medical sector for understanding the survival function by applying Kaplan Meier estimator and gave an overview of patients survival probability from the collected database. It involves computing of probabilities of occurrence of event at a certain point of time and multiplying these successive probabilities by earlier computed probabilities to get the final estimate.

F. J. G. Carazas, et. al. (2011) [61] presented a method for reliability and availability evaluation of Heat Recovery Steam Generator (HRSG) installed in combined cycle gas and steam turbine power plant. The method's first step consisted in the elaboration of the steam generator functional tree and development of failure mode and effects analysis. The next step involved a reliability and availability analysis based on the time to failure and time to repair data. The third step, aiming at availability improvement, recommended the fault-tree-analysis (FTA) development to identify the component failure. S. Kumar & P. C. Tewari (2011)[62] discussed the mathematical modelling and performance optimization of CO2 cooling system of a fertilizer plant. Differential equations had been derived based on Markov Birth-Death process using probabilistic approach. These equations were then solved using normalizing conditions to determine the steady state availability of the CO2 cooling system.

S. Kajal (2012) [63] studied the performance optimization for skim milk powder unit of a dairy plant at National Dairy Research Institute (NDRI). He also used probabilistic approach & Markov-Birth-Date Process to develop governing differential equation which is useful for developing proper maintenance strategy of the Dairy Plant. Pratesh Jayaswal & Hemant Singh Rajput (2012) [64] worked on the implementation of 5-S technique to enhance Overall Equipment Effectiveness in leaf spring manufacturing company. They mentioned that before improvement, the OEE was found to be 43%. But after the implementation of the above mentioned pillars, the OEE increased dramatically to a whooping of 68% and labour cost decreased up to 43%.The increase in OEE resulted not only in better productivity but also excellent resource exploitation, high quality products and enriched employee morale and motivation. A. K. Gupta & R. K. Garg (2012) [65] presented a paper on OEE improvement through TPM in an automobile manufacturing organisation. In 2012, K.N Nandurkar & S. Anand Relkar [66] focussed on continuous availability of reliable sophisticated equipment with precision to fulfil the need of the competitive market. They made a determined effort to measure and analyse existing overall equipment effectiveness of critical machinery producing important vehicle parts which are being used by a leading automobile company. Using MiniTab15 software, they performed experimentation on three factors and two levels of OEE. Finally they concluded that simulated values of the output will be beneficial information to industry. Pradeep Kumar, K.V.M. Varambally & Lewlyn L.R.

Rodrigues (2012) [67] reviewed the literatures to understand the underlying concepts of TPM. They found that the average values of OEE lay between the ranges of 15% to 60% against world class standards of 85% and total productivity (TP) laid between 0.09 to 0.34. Hence major causes resulting in the downtime and abatement in the productivity was highlighted by them. They conducted a comparative study between World Class industries with TPM and industries without TPM and henceforth identified the various problems leading to substantial decline in the overall efficiency of the industry. A. Jain, et. al. (2012) [68] implemented TPM for enhancing OEE of small scale industry. After observation and implementation of TPM, they concluded that OEE has been changed drastically.

Ravikant V. Paropate & Rajeshkumar U. Sambhe (2013) [69] worked on the implementation and evaluation of Total Productive Maintenance in a midsized Indian enterprise. They carried out the following case study at a cotton spinning plant to identify the extensive deficiency associated with equipment effectiveness. They intended to analyse the practical problems accomplishing TPM program and hence improved the effectiveness of critical machine by significant value. Dr. Jagathy Raj V. P. & Deepak Prabhakar P. (2013) [70] also again modified RCM over A-RCM for the betterment of industry. Ranteshwar Singh, Ashish M. Gohil & Dhaval B. Shah (2013) [71] proposed a research on TPM implementation in a machine shop. They investigated TPM on a company manufacturing automotive component. In a CNC machine shop, they used the OEE as a measure of success of TPM implementation. S. Prasanth Poduval & V.R. Pramod (2013) [72] explained the limitations in TPM implementation in industries. They tried to study the problems faced by the industries in improving their manufacturing processes through TPM. A. Bangar, Hemlata Sahu & Jagmohan Batham (2013) [73] worked on a research work for improving Overall Equipment Effectiveness in an Auto Industry by TPM implementation through Pareto analysis and Kaizen methodology. Their foremost goal of the work involved OEE improvement and its three parameters viz. availability, performance and quality. They reduced the production losses and improved the OEE of the industry up to 96% by redesigning the workforce and improving the maintenance function. D. Bose, et. al. (2013) [74] had undergo a brief study on the measurement and evaluation of reliability, availability and maintainability of a diesel locomotive rail engine on the basis of five years collected data with the help of statistical software Minitab15. They suggested a safety stock so that the maintenance process is not delayed and high reliability of the engine is achieved.

FirdosJahan Khan & T.Z Quazi (2014) [75] worked on the implementation of Kobetsu Kaizen pillar for improving Overall Equipment Effectiveness of machines. Furthermore they found that the pillar looks into all the losses, analyses the losses using various quality control tools and comes up with suggestions that need to be implemented to reduce recurring losses. Dr. Lewlyn L.R. Rodrigues & Kamath H. Nagaraj (2014) [76] developed a case study for total Production Management in Printing Industry. S. R. Vijaykumar & S. Gajendran (2014) [77] proposed a plan for Overall Equipment Effectiveness improvement in an injection moulding process industry. They succeeded in increasing the OEE from 61% to a substantially better 81% through implementation of availability, better resource utilisation, good quality products and enriching employee confidence. Sandeep Kumar & Pardeep Gahlot (2014) [78] applied Total Productive Maintenance in Auto sector of Sona-Koyo Group, Gurgaon. Their main area of concern was on quality product, product delivery time and product cost. They tried to implement TPM as a measure to increase availability of existing equipment thereby reducing the essence of further capital investment. They also studied the tangible and intangible benefits derived at various stages of TPM implementation. Ravee Phoewhawm (2014) [79] performed a case study on Kaizen as a learning tool for a management team. He studied that due to complexity of working system, management teams often face a challenge in administrating Kaizen.

Nilesh Ayane & Mangesh Gudadhe (2015) [80] performed a review study on improvement of Overall Equipment Effectiveness in construction equipments. They presented a perfect picture of large construction companies whose success depends heavily on resources like man, materials and sophisticated machineries which are responsible for producing outputs. Thus the heavy and light construction companies are merely distinguished by the effectiveness of the machineries. Shekhar Sahu, Lakhan Patidar & Pradeep Soni (2015) [81] of N.I.T, Bhopal worked on a research paper based on 5-S technique to improve Overall Equipment Effectiveness for upgrading production levels. They developed a model to identify a relationship among 5S, OEE and manufacturing productivity. S. Vigneshwaran , M. Maran & G. Manikandan (2015) [82] studied a literature review on the impact of TPM implementation. They tried to point out the tangible and intangible benefits obtained as a result of TPM implementation. Meet Lalkiya & Deepak K. Kushwaha (2015) [83] proposed a research on optimizing and analysing OEE through TPM in a cement industry. They made an attempt to measure and analyse OEE of machinery producing Pozolona Portland cement. The most influential factor among them and the relationship between availability, performance rate and quality rate were obtained by them through main effect plots and regression analysis. They finally used the counter plots and response surface method to find the optimized value of the three factors of OEE. V. M. Kalra, et. al. (2015) [84] showed in their paper that how major loss events are affecting different OEE metrics including utilization. They described the weekly OEE data of the system over a months and how this OEE data is changing due to different factors. Hence, they concluded that OEE calculations help in making improvements in productivity by gradual improvement of availability, Performance and utilization over the months and year. Mihir K. Shah, et. al. (2015) [85] discussed on the Lean system also known as Toyota production system which is comprises of different tools and technique which provide basis for Continuous Improvement in industry. They described how Lean tools, Time and motion study, TPM, 5's, Kaizen and Single Minute Exchange Die (SMED) etc are influencing for the improvement of the different systems. Amit S. Ingale, et. al. (2015) [86] discussed the necessity of TPM and how eight pillars of TPM are influencing the system's performance rate, availability, quality and its effectiveness. They also mentioned that how different barriers in TPM pillars are retarding the production rate. Pritam Kumr (2016) [87] in his Master Degree thesis explained the how Reliability is directly related with failure. He described availability and maintainability of the main conveyor system in underground Churcha coal mine. His reliability analysis is on the basis of preventive maintenance of every subcomponent in the interval of 52 hrs, 65 hrs, 60 hrs, 84 hrs, 98 hrs, 20 hrs and 112 hrs. N. C. Maideen, et. al. (2016) [88] presents a practical framework to implement OEE and a case study has been discussed to explain in detail each steps of proposed framework And this proposed framework consists of three major phase which can be identified as; Phase I: Define, Phase 2: Design and Phase 3: Implementation. It is seen that this framework is very much beneficial to the engineer especially the beginner to start measure their machine performance and later improve the performance of the machine. S. K. Eddosa & A. P. Singh (2016) [89] explained in their paper that defect rate of final products can be reduced through Statistical Process Control (SPC) Tools involving Cause-and-Effect Diagram & Pareto Analysis. SPC tool is implemented to improve the product quality, reduce process variability & defect rate.

S. Dey & M. Sethi (2017) [90] showed how Pareto analysis works and how it is used and applied to determine the topmost event which will help the managers to know the exact situation of the fault or event to take further necessary action. I. Etikan, et. al. (2017) [91] gives the complete overview of Kaplan-Meier statistical method of survival analysis and how it can applied to medical patients for determining the survival probability to make a comparison between groups of participants such as control group and treatment group. A. N. Kamerkar & M. M. Bhagwat (2017) [92] gave the brief study on time-motion analysis in chemical plant to analyze the performance of each step in production for establishing new standard form of work & method.

2.3 Status of research work at Printing Engineering Department, Jadavapur University, India

Some works have also been started at Jadavpur University, Department of Printing Engineering during early twenties. The studies made by Shalini [93] showed that the Risk Based Maintenance (RBM) strategy can also be applied to the printing press. She collected her experimental data for one month where she determined the risk index for maintenance planning. She analysed the failure rates of different components with the help of Minitab software for regression analysis. She also showed how reliability & availability of all the machines can be increased on the basis of preventive maintenance. She also took the help of Fish-Bone Diagram for analysing the major causes of failures & recommended different remedies for the existing failures.

Chapter 3

THEORY OF RISK BASED MAINTENANCE (RBM) METHODOLOGY & TECHNICAL AUDIT

3.1 Introduction

In this chapter, it has been described the basic theory of Maintenance and Risk Based Maintenance Methodology where brief detail of Failure Rate, Reliability, Survival Function, Availability, Total Productive Maintenance Technique, Overall Equipment Effectiveness, 5'S technique, Pareto analysis, Brainstorming etc are discussed. Moreover, regression analysis including Weibull distribution has also been discussed and it showed that Weibull distribution of failure probability influences the reliability and risk factors of an equipment. Further, for analysis of data collected different mathematical expression are studied here along with the pictorial representation. Also the theory of Technical Audit has been discussed here to study the performance of the machineries and the plant.

3.2 Maintenance

The maintenance is defined as the activity which is carried out for any equipment to ensure its reliability to perform its functions [94]. Actually, maintenance is the basic activity which carried out on an asset in order to ensure that the asset continues to perform its included functions or to repair any equipment that has failed or to keep the equipment running or to restore its operating conditions. Over the years, various plants & industries have implemented many new strategies of maintenance in order to overcome the failure problems which can be classified into four main categories, namely:

- Corrective / Breakdown maintenance,
- Preventive maintenance,
- Predictive maintenance,
- Proactive maintenance.

Further, any type of maintenance work can also be sub-divided into different subtypes or disciplines. They are given below:

- Condition-Based maintenance (CBM),
- Periodic maintenance (PM),
- Risk-Based maintenance (RBM)
- Reliability Centred maintenance (RCM) etc.

3.2.1 Corrective/Breakdown maintenance

It is the maintenance actions performed after failure of the item. It is the actions necessary to restore the process or equipment back to running or operating state. The actions are properly performed by repair or replacement of components (or subsystems randomly) because it is impossible to identify the specific failure time [95]. This strategy has no routine maintenance task and also described as no schedule maintenance strategy.

3.2.2 Preventive maintenance

This is time-based maintenance strategy where on a predetermined periodic basis, equipment is taken off-line, opened up and inspected [95]. Based on visual inspections, repairs are made and the equipment is then put back on-line. Thus equipment maintenance strategy, replacing, overhauling or remanufacturing an items is done at a fixed interval of time. Hence it is necessary for periodic maintenance of equipment to reduce the breakdown.

3.2.3 Predictive Maintenance

Predictive maintenance is more condition-based approach to maintenance. The approach is based on measuring of an equipment condition in order to assess whether equipment will fail during some future period and then taking action to avoid the consequences of that failures. This is where predictive technologies (i.e. vibration analysis, infrared thermographs, ultrasonic detection etc) are utilized to determine the condition of equipment and to decide on any necessary repairs. Apart from the predictive technologies, statistical process control (SPC) techniques, equipment performance monitoring or human senses are also adapted to monitor the equipment condition. This approach is economically feasible strategy as labours, materials and production schedules are used much more efficiently.

3.2.4 Proactive Maintenance

Unlike the three types of maintenance strategies which have been discussed earlier, proactive maintenance can be considered as new approach to maintenance strategy. Dissimilar to preventive maintenance (which is based on time intervals) or predictive maintenance (which is based on condition monitoring), the Proactive maintenance mainly concentrate on the monitoring and correction of root causes to equipment failures. This types of strategy is also designed to extend the useful age of the equipment to reach the wear-out stage by adaptation a high quality of operating precision.

The above maintenance methods are summarized below in Table 3.1.

Table 3.1: Different Maintenance Strategies & its significance

MAINTENANCE STRATEGY	**MAINTENANCE APPROACH**	**SIGNIFICANCE**
Corrective/Breakdown Maintenance	Fix it when broke	Large maintenance budget.
Preventive Maintenance	Scheduled Maintenance	Periodic component replacement.
Predictive Maintenance	Condition based Monitoring	Maintenance decision based on equipment condition.
Proactive Maintenance	Detection of sources of failures.	Monitoring and correcting root causes of failure.

3.3 Maintainability

Maintainability is defined as the ability of an item under given conditions of use, to be retained in or restored to a state in which it can perform a required function. It is the probability that a given active maintenance action for an item can be carried out within a stated time interval [87].

Moreover, from the statistical point of view it can be explained that the time to repair (T) of an item is defined as a continuous random variable & this random variable will have a Probability Density Function (PDF) parameter like the reliability function. Obviously, maintainability addresses the probability that the repair has happened, and therefore the maintainability M(t), which is a function of time t, is expressed as in equation 3.1 [96]:

$$M(t) = P(T' \leq t) = F'(t) \quad ....(3.1)$$

Where F'(t) is the Cumulative Density Function (CDF) of the time to repair and T' is the random time to repair variable.

In other words, the probability that the item will be repaired within a specific time t is known as maintainability. If a system has a maintainability of 80% per day, that means there is 80% probability that the system will be restored or repaired within a day. The PDF for the maintainability is denoted f'(t), then the maintainability function M(t) can be further expressed as in equation 3.2 [87]:

$$M(t) = \int_0^t f'(t)dt \quad ....(3.2)$$

Where f'(t) is defined to be the probability distribution for the specific repair time.

In simple words, maintainability is the probability that a unit or system will be restored to specified condition within a given time-period. In the duration of maintenance, equipment's design will set maintenance procedures & resources to evaluate the length of repair time. Thus, it is often compared or referred to MTTR i.e. mean time to repair or the limit of max repair time.

From the qualitative point of view, it refers to the ease with which hardware or software is restored or in fully functional condition. Again, from the quantitative point of view it refers the probabilities and the measurement based on total down time i.e. the time taken for diagnosis, trouble shooting, tear-down, active repair time, verification of testing that the repair is adequate, removal or replacements, delay for administrative maintenance & logistic movements etc. In case of exponential [96] & Weibull distribution [92] Maintainability M(t) can be expressed by the equation 3.3 and equation 3.4 respectively which are given below:

$$M(t) = 1 - e^{-\mu t} \quad ....(3.3)$$

$$M(t) = 1 - e^{-(\mu/\eta)^{\beta}} \quad ....(3.4)$$

Where, " $\frac{1}{\mu}$ " is repair time or mean time to repair , " t " is operating time or mean operating time, "β" is shape factor and "Ƞ" is scale factor.

3.4 Availability

Availability can also be defined as the probability that a system or component is performing its required function at a given instant of time or over a stated period when operated and maintained in a prescribed manner [97]. That is the probability that a system is not failed or undergoing repair action on when it needs to be used. Therefore, the availability of a system is given in equation (3.5) below:

$$\text{Availability (A)} = \text{MTBF}/(\text{MTBF} + \text{MTTR}) \quad ....(3.5)$$

It is possible to define three types of availability depending on time element where MTBF indicates mean time between failures.

3.4.1 Inherent availability

Inherent availability is the probability that a system or equipment, when used under stated conditions, is an ideal support environment (i.e., readily available tools, spares, maintenance personnel, etc.), which will operate satisfactorily at any point in time as required [97]. It is the function of preventive or scheduled maintenance action, administrative delay time & logistic delay time, and it is expressed as in equation 3.6 [99]:

$$A_{in} = MTBF / (MTBF + MTTR) \quad ....(3.6)$$

Where, MTBF is defined as the mean time between failures whereas MTTR is defined as the mean time to repair. In this context, it is important to note that the Inherent availability is based solely on the failure distribution and repair time distribution.

3.4.2 Achieved availability

Achieved availability is the probability of a system or equipment, when used under stated conditions is an ideal support environment (i.e., readily available tools, spares, personnel, etc.), which will operate satisfactorily at any point in time. The achieved availability is defined as in equation 3.7 [97]:

$$A_a = MTBM / (MTBM+MDT) \quad ....(3.7)$$

Where, MTBM is the mean active maintenance downtime resulting from both preventive & corrective maintenance and MDT is mean downtime.

3.4.3 Operational availability

Operational availability is the probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily. The operational availability is defined as in equation 3.8 [97, 98]:

$$A_{op} = MTBF / (MTBF + MDT) \quad ....(3.8)$$

Where MDT is the mean downtime that includes restoration delay time, logistics delay time and administrative delay time.

In general the availability of a system is a complex function of reliability maintainability and supply effectiveness. This can be expressed as in equation 3.9 [99];

$$A_s = f\,(R_s,\ M_s\ ,\ M_s) \quad ....(3.9)$$

Where, A_s = System availability, R_s = System reliability, M_s = System maintainability, M_s=Supply effectiveness.

3.5 Downtime

Downtime is defined as the duration of time for which a system under consideration fails to perform its primary functions in an appropriate way. Reliability, availability, recovery & unavailability are the related concepts. It is the proportion of time-span that a system is unavailable or offline. This is usually a result of the system failing to function because of an unplanned event or a planned event or routine maintenance. There are three types of downtime, namely [97]:-

- **Restoration delay time:** It is the time that spent for corrective or preventive maintenance actions from breakdown.
- **Administration delay time:** It is the duration of downtime due to any form of procedural or regulatory requirements.
- **Logistics delay time:** It is downtime that is associated with the restoration operation for making replacement of necessary parts/tools.

3.6 Risk-Based Maintenance (RBM) Methodology

The basic aim of maintenance strategy is to minimize hazards which are caused by the unexpected failure of the equipment. To increase the machine's life and to reduce the risks caused by failure of the equipment, Risk-based approaches are used in present days. Generally, these types of risk-based approach use the information that is obtained from the study of failure modes and their economic consequences. Moreover, it is important to note that these approaches are very cost effective. This approach includes RBM methodology, RAM methodology, TPM methodology etc.

Risk-based approach is a technique for identifying, characterizing, quantifying, and evaluating the loss from an event. Risk analysis approach integrates probability and consequence analysis at various stages of the analysis and attempts to answer the following questions [14]:

- What can go wrong that could lead to a system failure?
- How can it go wrong?
- How likely is its occurrence?
- What would be the consequences if it happens?

Risk assessment can be quantitative or qualitative. The output of a quantitative risk assessment will typically be a number. The number (i.e. cost impact per unit time) could be used to prioritize a series of risked items. Risk can be written as shown in equation 3.10:

$$\text{Risk} = (\text{Failure Probability}) \times (\text{Consequence of Failure}) \quad \text{.............(3.10)}$$

Quantitative risk assessment requires a great deal of data both for the assessment of probabilities and assessment of consequences. Fault tree or decision trees are often used to determine the probability so that a certain sequence of events will result in a certain consequence.

Qualitative risk assessment is less rigorous and the results are often shown in the form of a simple risk matrix where one axis of the matrix represents the probability and the other represents the consequences. If a value is given to each of the probability of failure and a consequence, then a relative value for risk can be calculated.

The proposed risk-based maintenance (RBM) strategy aims at reducing the overall risk of failure of the operating facilities. In areas of high and medium risk, a focused maintenance effort is required. The quantitative value of the risk is used to prioritize inspection and maintenance activities. RBM suggests a set of recommendations on how many preventive tasks are to be performed. The implementation of RBM will reduce the likelihood of an unexpected failure [14].

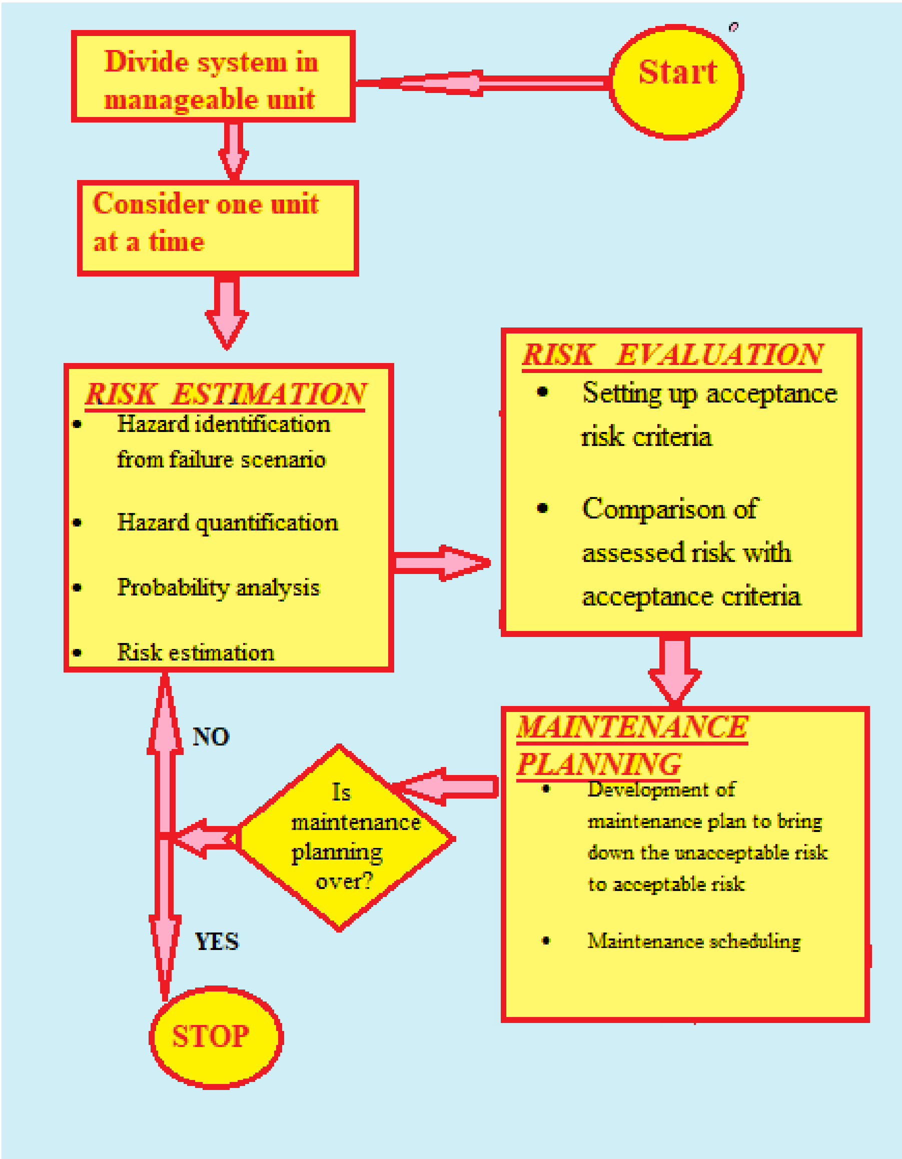


Fig 3.1: Flow diagram of RBM architecture

The architecture of risk-based maintenance methodology is described in Figure 3.1. The RBM methodology is comprised of following three main modules which are interactively linked.

- Risk Determination (which consists of risk identification and estimation),
- Risk Evaluation (in where acceptance criteria are set to compare with existing Risk)

- Maintenance Planning (in where reduction of risk level is executed by the help of proper planning)

3.6.1 Risk Determination or Estimation

Risk determination or estimation is the first module of RBM architecture. Estimation of risk is comprised of four sub-steps which are logically shown in Figure 3.2 . The four steps are Failure Scenario Development, Hazard Quantification or Consequence Assessment, Probabilistic Failure Analysis and Risk estimation.

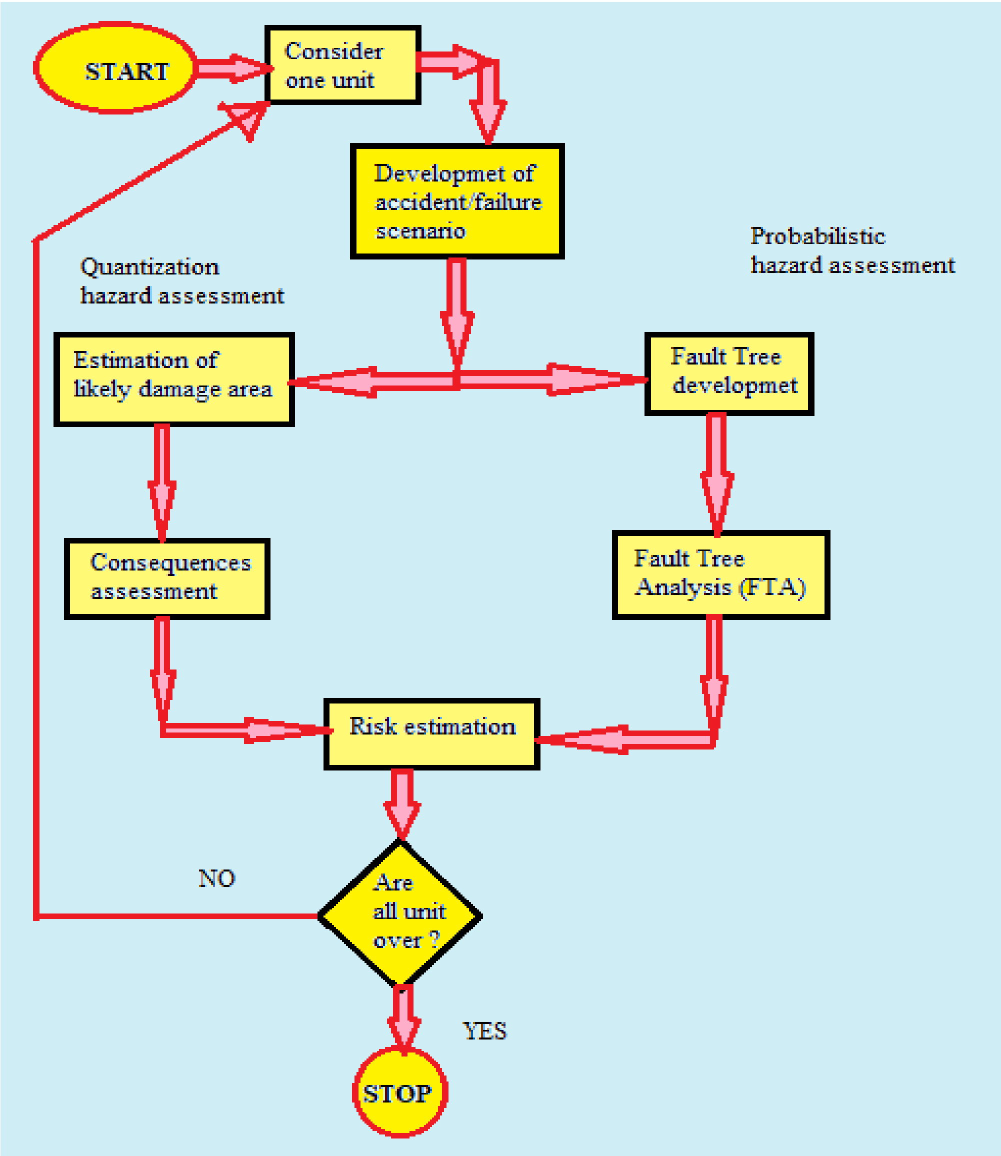


Figure 3.2: Flow diagram of Risk Determination or Estimation

Failure Scenario Development or Hazard Identification:- A failure scenario is a description of a series of events which leads to a failure system. It may contain a single event or a combination of sequential events. Usually, a system failure occurs as a result of interacting sequence of events. A failure scenario is on the basis of risk study & it tells us what may happen, so that we can develop different ways & means for preventing or minimizing the probability of its occurrence.

Hazard Quantification or Consequence Assessment:- The objective of consequence assessment is to quantify the potential consequences of the total-functional-failures on the basis of their contribution to a system failure. The analysis involves assessment of likely-consequences if a failure scenario materializes. The total consequences assessment is a combination of four major categories of consequences, namely System Performance Loss, Financial Loss, Human Health Loss and Environmental Loss [14].

Probabilistic Failure Analysis:- It is conducted by using Fault-Tree-Analysis (FTA). One can use FTA along with component-failure-data to determine the frequency of an occurrence of an event/failure and availability of a unit [14]. The key features of this step are FTA analysis, Probability analysis which are described below:

- Fault Tree Analysis (FTA): During fault tree development, the top event (failure) is identified on the basis of process, control arrangement and behaviour of components of the unit/plant. Based on the estimation of risk top events are arranged in FTA analysis.

- Probability Analysis: To increase the accuracy of the computations and to reduce the margin of error due to inaccuracies involved in the reliability of data of the basic events (initiating events), it is suggested that Weibull distribution function should be used. Weibull analysis (described later in Reliability Analysis) is the statistical analysis or tool used to determine the system’s failure probability (frequency of occurrence of an event) and availability of a unit.

Risk estimation:- The results of the consequence and the probabilistic failure analyses are finally used to estimate the risk that may result from the failure of each unit. Based on the results of consequence analysis and probability analysis the risks posed by each unit are estimated. Thus the level of calculated risk reflects the total risk for the system and calculated risk is evaluated against the acceptance-criteria during Risk Evaluation

3.6.2 Risk Evaluation

Risk Evaluation is the second module of RBM architecture. The objective of Risk Evaluation is to calculate the estimated risk using the methodology explained above. This evaluation algorithm comprises of two steps namely Setting-up an Acceptance Criteria and Risk comparison against Acceptance as shown in Figure 3.3. The algorithm used is shown in the Flow Diagram (Fig. 3.3) where risk evaluation is focused on mainly Setting-up an Acceptance Criteria and Risk comparison against Acceptance Criteria, which are described below.

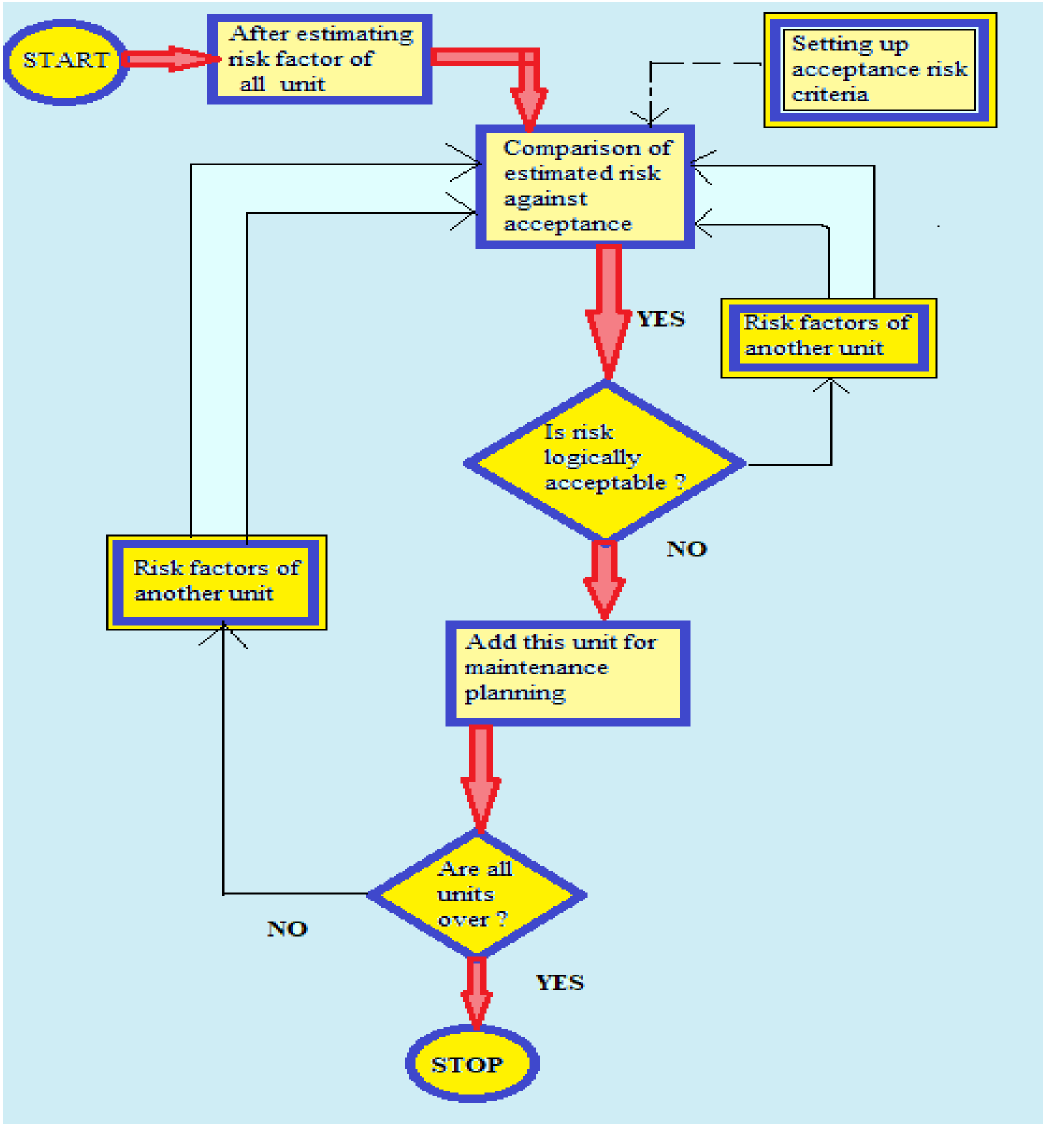


Figure 3.3: Flow diagram of Risk Evaluation

Setting-up an Acceptance Criteria:- In this step the specific risk acceptance criteria is identified. To allow for different criteria of the acceptable level of risk depending on the system nature and type, an open-ended methodology should be used. Different acceptance risk criteria are available in the literature, see ALARP (as low as reasonably possible) (where residual risk are reduced), Dutch acceptance criteria, and USEPA acceptance criteria (14).

Risk comparison against Acceptance Criteria:- In this step, estimated risks are compared with the risk acceptance criteria setup earlier. A component whose risk exceeds the acceptance criteria is marked for further analysis to reduce risk and it is repeated for all the units of the system.

3.6.3 Maintenance Planning

It is the final module of RBM architecture where reduction of risk level is executed through maintenance planning [97]. This module comprises of two steps which are logically linked is shown in Figure (3.4) below:

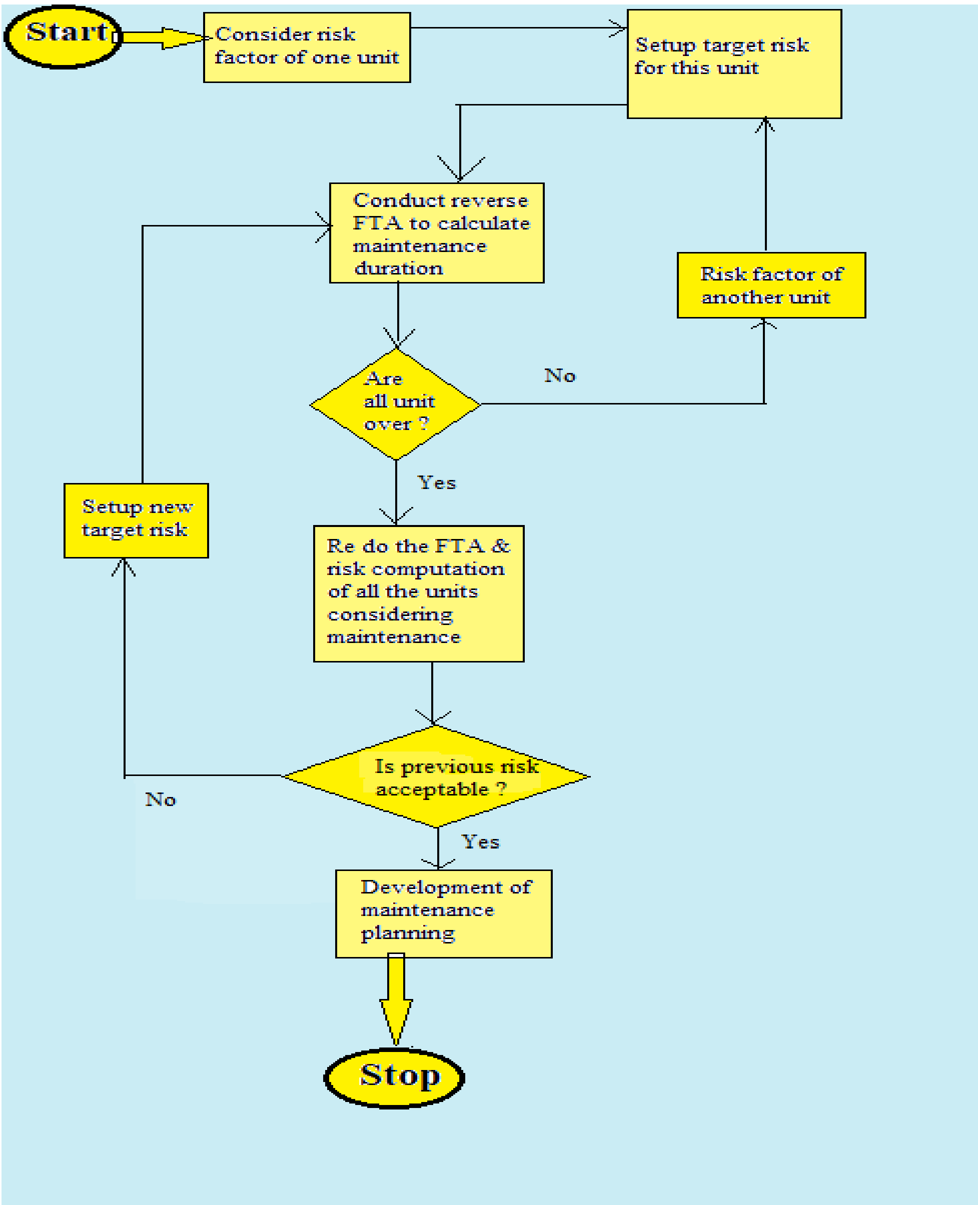


Figure 3.4: Flow diagram of Maintenance Planning

From the above figure it is clear that maintenance planning are executed by estimating the maintenance duration and further re-estimating & re-evaluating the corresponding risk.

Estimation of Maintenance Duration: Every failure & their causes are studied in detail to determine the probability of failure adversely. Then, the reverse fault tree analysis is carried out to determine the required value of the probability of failure of the basic event. The new probabilities of the failures of the basic events will be used to calculate the corresponding maintenance interval.

Re-estimation & Re-evaluation of Risk: The last step in this methodology is aimed to verify that the maintenance plan developed produces acceptable total risk level for the existing system. The result of these steps will clearly indicate whether the developed maintenance plan is effective or not to manage the risk.

3.7 Failure Analysis

Failure is an event that affects not only a system but the system criteria also. The system criteria include finished output maintenance cost or capital cost, safety etc. On a given system the failures may change with the change of time. Failures do not generally occur at a uniform rate, but follow a specific distribution in time which is commonly known as a "Bathtub Curve" [74] shown in Figure 3.5. The life of a device can be divided into three regions, namely (i) Infant Mortality Period, where the failure rate progressively improves; (ii) Useful Life Period, where the failure rate remains constant & (iii) Wear out Period, where failure rates begin to increase.

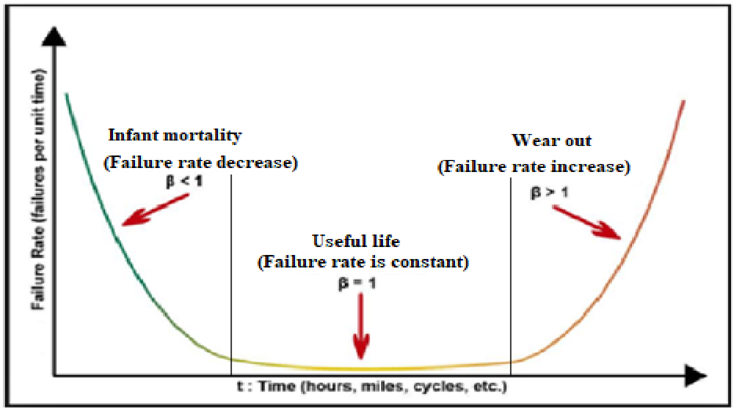


Figure 3.5: Bath-tub curve of a system describing failure rates at different periods.

Failure distribution is very much important parameter in order to take decisions whether it will lead to the change or modification of design of a system to minimize the overall cost or maximize a system performance within the allowable financial budget and other performance-based constraints. The goal of a system modelling is to provide quantitative forecasts or details of various system performance measures such as downtime, availability, number of failures, capacity and cost.

It is very much important to note that two important factors are taken into account in this analysis which are the failure and repair behaviours of the system. The failure and repair rates of components are often defined in terms of distributions or how the failures and repairs occur in between or after or before the operational time.

The technique of a visualization of characteristics of a failure or repair distribution is to use the Probability Density Functions (PDF) and it depends upon the component's failure mechanism or repair mechanism. Several methods are used to determine the distribution that best fits a given failure or repair pattern.

It is also important to note that failure probability is also termed as an unreliability in failure analysis. Moreover, it is observed that if the type of distribution is not known in advance, then the distribution that best fits the failure or repair times can be found using different statistical methods. Anderson-Darling (AD) test is used to find best-fit or goodness-of-fit tests. However, it is pertinent to say that the above stated test can be implemented with great ease by the use of software tools or Weibull analysis tools like MINITAB-17, Easyfit etc [87].

3.8 Reliability analysis

Reliability is defined as the ability of an item to perform a required to perform required function under given conditions for a given interval of time. Reliability can also be described as the probability that an item (component, system, or subsystem) or process operates properly for a specified amount of time under stated conditions (both environmental and operational conditions) without failure [87].

The reliability function can be derived from the cumulative distribution function ‘F(x)’. So, the Cumulative Density Function is the probability that the random time to failure ‘T’ is less than or equal to the operating time ‘t’. The cumulative density function (CDF) for reliability is denoted as ‘F(t)’ which is also related to failure probability and in combination with the fact that the area under the probability density function (PDF) is always equal to 1 [87]. Obviously, the reliability function can be expressed as in equation 3.11 :-

$$R(t) = 1 - F(t) \quad ....(3.11)$$

The relation between the CDF and the PDF is given in equation 3.12 :-

$$F(t) = \int_0^t f(t)\, dt \quad ....(3.12)$$

where, f (t) is probability density function (PDF) of time to failure.

The reliability function R(t) can be written as:-

$$R(t) = 1 - \int_0^t f(t)\,dt = \int_t^\infty f(t)\,dt \quad ....(3.13)$$

where, f (t) is probability density function of time to failure.

3.8.1 Survival analysis (Kaplan Meier Estimation) for Reliability

Kaplan-Meier (KM) method is one of the most widely used statistical methods used in the analysis of time to event data. It is pertinent to mention that KM method is a non-parametric estimation for Survival Function (S_t) (or Survival Probability). KM Estimation is found to be a simpler procedure in order to find the survival rate with respect to time in spite of all the difficulties associated with the subjects, situations & failures to determine the survival probability [91]. The mathematical expression of survival function (S_t) is given in equation 3.14 :

$$S_t = \frac{[(\text{No.of subjects living at the start}) - (\text{No.of subjects died})]}{(\text{No.of subjects living at the start})} \quad ....(3.14)$$

This equation is valid for the survival of public health. The validity of this equation can also be extended to the print production and the equation can be re-written.

$$S_t = \frac{[(\text{No. at Risk}) - (\text{No. failed due to its corresponding time})]}{(\text{No. at Risk})} \quad ....(3.15)$$

3.8.2 Graphical evaluation for Reliability prediction

There are many ways for graphical evaluation of reliability prediction, namely normal plotting, exponential plotting & Weibull plotting. The normal distribution plotting is widely used in all the general distributions. Since the normal distribution approximates many natural phenomena in a proper way hence it has developed a standard of reference for many probability problems in which two parameters are used. The mathematical formulation of probability density function (PDF) for normal distribution plotting is given in equation 3.16 [87]:

$$f(t) = \{1/\sigma\sqrt{(2\pi)}\}\, e^{-[\frac{(t-\xi)^2}{2\sigma^2}]} \quad ....(3.16)$$

where, ‘ξ’ is the mean of time between failure (MTBF), ‘σ’ is the standard deviation of MTBF.

Exponential distribution is very important because of its constant failure rate “λ”. Generally, this distribution is widely used for modelling the lifetime of both the mechanical and electrical components of a system. The mathematical expression of probability density function (PDF) of the exponential distribution is given in equation 3.17 [87]:

$$f(t) = \lambda\, e^{-\lambda(t-\gamma)} \quad \text{.............(3.17)}$$

where, "γ" is the location parameter

When the failure rate is constant, the distribution follows exponential probability law and when failure rate is not constant (i.e. non-linear hazard model) follows Weibull distribution which is described later, in Art. 3.9.

As the collected data for the failures of different components of the Printing Press (given in Chap. 4, Art. 4.2) shows that the failure rates of the components are not constant, the Weibull distribution models are adopted in the present study.

Moreover the technique of Anderson-Darling (A-D) test & linear regression analysis confirms the suitability to use Weibull distribution for the different components or sub-components of the Printing Press. The analysis determines the best-fit line in the least square sense [74]. The least square test has been used to obtain the rate of failure. Linear regression analysis has been carried out by using the following Probability equation.

$$R_{x,f(x)} = \frac{p}{q} \quad \text{.............(3.18)}$$

where,

$$p = \Sigma\{xf(x)\} - \frac{\{\Sigma x * \Sigma f(x)\}}{N} \quad , \quad q = \sqrt{\left[\Sigma(x^2) - \frac{(\Sigma\, x)^2}{N}\right]\left[\Sigma\, f(x^2) - \frac{\{\Sigma\, f(x)^2\}}{N}\right]}$$

x = breakdown hour (in minute or sec)

Y = f(x) = Cumulative % failure

N = no. of trials

$R_{x,f(x)}$ = Correlation coefficient

Failure data of the different components or sub-components of the Printing Press is used for determining the correlation co-efficient. From the concept of probability, it is known that the correlation coefficient must be in between +1.0 to -1.0. If the correlation coefficient estimates positive value, then the failure rate is increasing, otherwise the rate is decreasing and so Weibull distribution is applied for the estimation of reliability of the different components or sub-components of the Printing Press.

3.9 Weibull distribution

Among all of the available distributions for reliability calculations, the Weibull distribution is the only unique method. Allodia Weibull (1887-1979) [100] stated that normal distributions are not applicable for characterizing initial metallurgical strengths during his study on metallurgical failures. He then introduced a function and used seven different case studies to demonstrate how the function allowed the data to select the most appropriate distribution from a broad family of Weibull distributions. To the best of the knowledge it is the most widely used distribution in reliability engineering and the failures caused by fatigue, corrosion, mechanical abrasion, diffusion and other degradation processes can be easily analyzed.

The Weibull distribution with 3-Parameter is largely used in reliability and life data analysis due to its versatile industrial application. Weibull distribution is used to model a variety of life behaviours, where "β" is the shape factor and "Ƞ" is the scale factor. These factors are essential to study the distribution characteristics of reliability and failure rate. The general form of the Weibull distribution, (i.e., the 3-parameter form) is assumed [87]. The appropriate substitutions are needed in order to obtain the 2-parameter form wher the location parameter γ = 0 and 't' is the time parameter. Probability density function (PDF) for Weibull 3-parameter distribution is given by equation 3.19:

$$f(t) = [\ (\frac{\beta}{\eta})\ .\ \{\frac{(t-\gamma)}{\eta}\}^{\beta-1}\ ]\ e^{-\{\frac{(t-\gamma)}{\eta}\}^{\beta}} \quad ....(3.19)$$

Therefore, the probability density function for Weibull 2-parameter distribution is obtained by putting γ = 0 in equation 3.19 and given by equation 3.20:

$$f(t) = [\ (\frac{\beta}{\eta})\ .\ \{\frac{t}{\eta}\}^{\beta-1}\ ]\ e^{-\{\frac{t}{\eta}\}^{\beta}} \quad ....(3.20)$$

It is obvious that, two parameter Weibull distribution requires characteristic life (η) and shape factor (β) values. 'β' determines the shape of the distribution. If 'β' is greater than 1, the failure rate is increasing. If 'β' is less than 1, the failure rate is decreasing. If β is equal to 1, the failure rate is constant. There are several ways to check whether data follows a Weibull distribution or not; the best choice is to use a Weibull analysis software. If such a tool is not available, data can be plotted manually to get Weibull probability plotting which determines wheather it follows a straight line or not. A straight line on the probability plot of regression analysis indicates that the data is following a Weibull distribution.

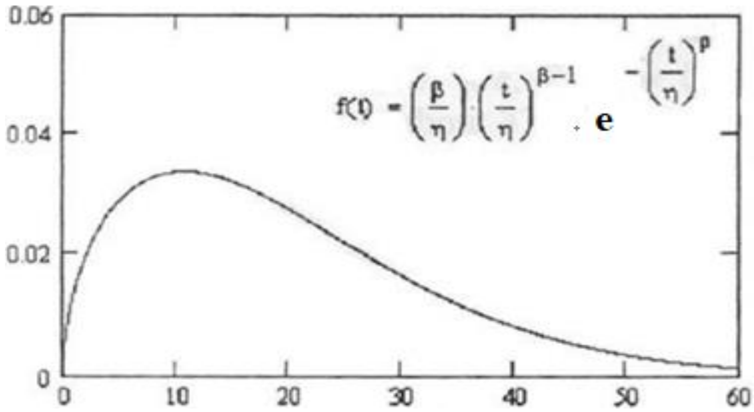


Figure 3.6: Weibull Distribution

Reliability analysis of the selected components can be summarized in terms of Weibull shape parameter. A basic diagram for Weibull distribution is shown in above Figure 3.6. Shape parameter is the indicative of the possible failure mechanisms and the causes of failures of any component. Table 3.2 shows the classification of shape factor according to their values.

Table 3.2: Classification of shape parameter (β)

Shape parameter	**Possible failure mechanism**	**Causes of failure**
$\beta > 1$	Age related pattern	Accelerated wear & tear of components
$\beta = 1$	Time independent pattern	Process error, design fault, malfunction of process
$\beta < 1$	Early failure	Manufacturing failure & reconditioning fault

3.10 Total Productive Maintenance (TPM)

TPM is Japanese approach for creating company culture for maximum efficiency, striving to prevent losses with minimum cost (zero breakdown & failure, zero accidents & zero defects) and involvement of all people from top management to operator. TPM initiatives as suggested by the Japan Institute of Plant Maintenance (JIPM), involve an eight pillar implementation plan that results in substantial increase in labour productivity through controlled maintenance, reduction in maintenance costs and reduced production stoppages & downtimes. The JIPM eight pillar TPM implementation plan is described in Figure 3.7 where P1, P2, P3, P4, P5, P6, P7 & P8 are the respective TPM pillars. Table 3.3 shows detailed maintenance and organizational improvement initiatives, activities & benefits [68].

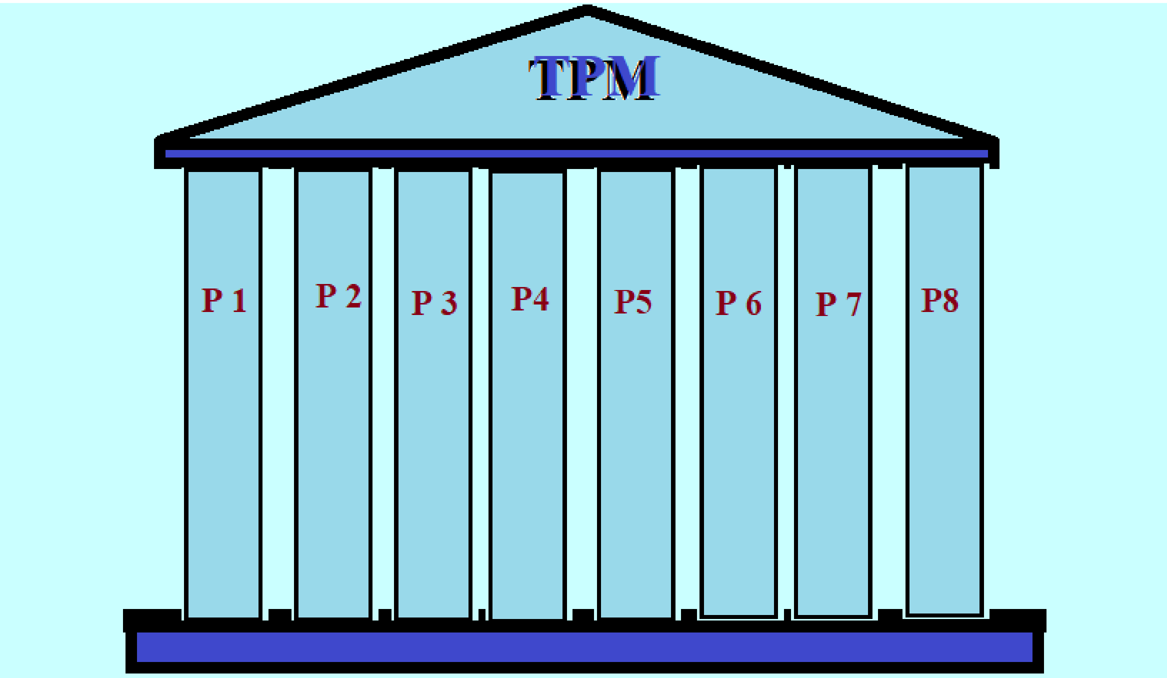


Figure 3.7: Architecture of 8 pillar of TPM

Table 3.3: Eight pillar of TPM indicating relevant benefits

Level/Pillar	**Description of every Level/Pillar**
Autonomous Maintenance (P1)	Responsible for basic maintenance activities performed by the skilled operators by cleaning, lubricating, tightening, adjustment, inspection, readjustment on production equipment. **Benefits**: Workers become more responsible and reduction in downtime by small-small improvements (i.e. step by step improvement)
Focused Improvement(P2)	OEE improvement by identification & elimination of all types of losses **Benefits**: Large base of employees with right tools for solving problems
Planned Maintenance (P3)	Establishment of different maintenance plans like preventive maintenance, predictive maintenance systems etc for equipment life cycle for the improvement of MTBF, MTTR etc. **Benefits**: Breakdown reduces

Quality Maintenance (P4)	Tracking & addressing of equipment problems & their root causes [68] by setting of "Ishikawa diagram or FBD analysis" for controlling & interaction between men, material, machine & methods. **Benefits**: Defect are minimized by providing input of right qualities to the machines under consideration & workers in order to achieve a permanent solutions in the context of quality management point of view
Education & Training (P5)	Development of quality control & interpersonal skills, implement of technology, Periodic skill evaluation & updating, Companywide initiative including all levels from operators to managers. **Benefits**: Successful implementation of TPM
Safety & environmental/ occupational health (P6)	Provide standard operating procedures and appropriate safe working culture & environment to eliminate injuries & accidents. **Benefits**: Tends to Zero accidents, Zero overburden & Zero Pollution in collaboration with various eco-toxicological aspects on ageing.
Office TPM (P7)	Improvement of various business function, removal of procedural hassles, focus on addressing cost-related issues, implementation of "5's or Kaizen process" in office & working areas, Utilize learning from existing systems to new system. **Benefits**: Improves order processing procedures and quick reactions to changing customer requirements
Development management (P8)	Utilize learning from existing systems to new systems maintenance improvement initiatives for the optimal running in time and minimization of failures on new equipment. **Benefits:** Improvement of OEE.

3.11 5s or Kaizen Process

Kaizen is a Japanese word that says small improvement of process in a continuous way of the standard flow of process & work. The word "Kai" means change and "Zen" means for the better i.e. "change for the better" [85]. The Kaizen activity is used to:

- Standardize an operation and activities.
- Measure the standardized operation (find cycle time and amount of in-process inventory)

- Innovate to meet requirements and increase productivity
- Standardize the new, improved operations
- Continue cycle

Kaizen process is widely known as the Deming cycle or PDCA (Plan do check & Act) where Kaizen process related activities are needed in order to achieve the "product performance" and reduce the "cost". Obviously, it is a powerful approach for any company/organization for assuring the target oriented value at a low but profitable budget/price for the customer.

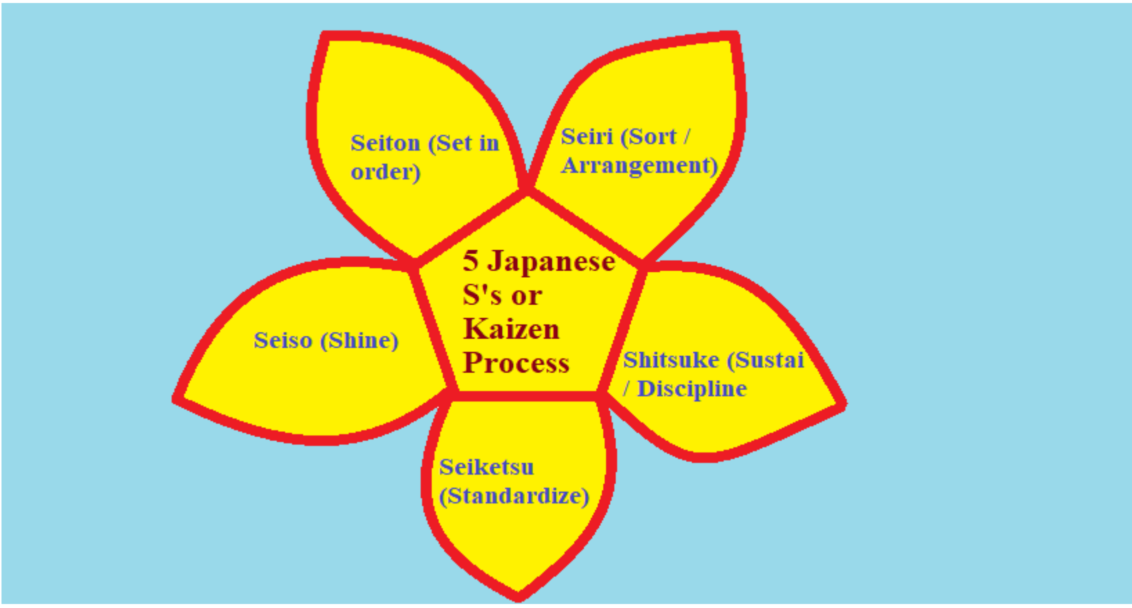


Figure 3.8: 5'S Techniques of Kaizen process

5'S is also used to describe the various components of Kaizen process [85] namely Seiri, Shitsuke, Seiketsu, Seiso & Seiton as shown in Figure 3.8:-

- **Sort or arrangement (Seiri) :** The 1st S (Sort), calls for the elimination of unnecessary items, debris and unused objects etc to overcome the worse scenario work-place & to increase productivity.
- **Set in order (Seiton) :** After sorting or completion of Seiri process, all devices or element should be set in order i.e. the Seiton process should be implemented which focuses on effective storage and organization methods, with the end goal of developing an environment that resists clutter and aids long-term productivity.
- **Shine (Seiso) :** Once the elimination of the clutter in the work area is done, it is important to thoroughly clean that area and the equipment in it. Clean workplace conditions are also important to employee health, morale, and safety.

- **Standardize (Seiketsu) :** Implementation of previous system without established standards tend to lose effectiveness with time. So the employees should be allowed to participate in the development of standards that improve workplace conditions. And it is advisable that employees should give feedback to find the best way to increase employee's morale with production concerns.
- **Sustain or discipline (Shitsuke) :** It is observed that Shitsuke is the most difficult "S" to implement and achieve. People has a tendency to resist change and the most well-structured 5'S plan will fail if not constantly reinforced. Fortunately, there are effective methods of sustaining positive growth.

3.12 Brainstorming Session, Ishikawa analysis & Pareto analysis:

Brainstorming Session:- Brainstorming is a most popular technique used to elicit a large number of ideas from a team using its collective power. The brainstorming procedure and rules were initially taught to the team members at department level as in order to establish the cause-and-effect diagram for better understanding the exact situations under certain specified conditions. The team leader is only responsible to make a structured questionnair. Team leader is responsible to put down all ideas & constructive remarks as indicated by cause-and-effect diagram. The cause-and-effect diagram usually comes from a brain storming session. Other result of brainstorming session is the Pareto chart which helps to prioritize the efforts and focus attention on the most prioritized problem.

Ishikawa analysis:- Ishikawa analysis is also known as Causes-and-Effect diagram or Fishbone diagram(FBD).The variables which are identified during brainstorming session, are logically summarized by the Ishikawa fishbone diagram [89]. This method was used to determine which variables cause the acute problem for the production process in any manufacturing organisation including Printing Press. Generally the goal, problem, failure or breakdown are fitted in the head of the fish skeleton as an "EFFECT", where as several "CAUSES" are fitted to the different branches/parts of the remaining fish skeleton. In this connection it is pertinent to note that the several main factors like raw material, method, machine, people-involved and industry-environment are considered in order to find the probable causes.

Pareto analysis:- Pareto chart can be used to display categories of problems graphically so they can be properly prioritized. The Pareto chart is named for a Italian Economist who postulated that a small minority (20%) of the people owned a great portion (80%) of the wealth in the land. A Pareto chart or diagram indicates which problem to tackle first by showing the proportion of the total problem that each of the smaller problem comprise. This is based on the Pareto principle: 20% of the source causes 80% of the problem. It is nothing but vertical basic graph displaying rank in descending order of importance for the categories of problems, defects or opportunities. Generally, one can gain more by working on the problem identified by the tallest bar than trying to deal with the smallest bars.

3.13 Overall Equipment's Effectiveness (OEE) Analysis

The effectiveness of facilities is its best possible return generated & calculated as percentage of each group of six big losses which is proposed by Japanese Technocrat Nakajima. The six big losses are breakdown, set-up & adjustments, small stops, reduced speed, production rejects or scraps and start-up losses. The definition of six big losses has been [88] described and given in Table 3.4 for ready reference.

Table 3.4: Six big losses

Losses	Definition	Mapping with OEE
Equipment breakdown	Time losses & quantity losses caused by defective products	Availability loss
Set-up and adjustment	Time losses resulting from downtime and defective products that occur when production of one item ends & the equipment is adjusted to meet the requirements of another item	Availability loss
Idling & minor stop	Production is interrupted by a temporary malfunction or when a machine is idling	Performance loss
Reduced speed	Difference between equipment design speed and actual operating speed	Performance loss
Reduced yield	Occur during the early stages of production from machine start up to stabilisation	Quality loss
Quality defect & rework	Occur during the early stages of production from machine start up to stabilisation	Quality loss

The identified losses can be measured in terms of overall equipment effectiveness (OEE) which is a function of availability (A), performance rate (P) and quality rate (Q) as given in equation 3.21:

$$\text{OEE} = (\text{Availability\%}) \times (\text{Performance rate\%}) \times (\text{Quality rate\%}) \quad \text{.............(3.21)}$$

The identified losses are again mapped to the measuring of effectiveness as shown in Table 3.4. The definitions for availability (A), performance rate (P) and quality rate (Q) are available in the open literature. In the present study the following definitions are used.

$$\text{Availability} = \left\{\frac{(\text{Planned production time} - \text{Unplanned downtime})}{\text{Planned production time}}\right\} .100\% \quad \text{.............(3.22)}$$

$$\text{Performance} = \{ \frac{\text{Actual production output}}{\text{Expected production output}} \} .100\% \quad ....(3.23)$$

$$\text{Quality} = \{ \frac{\text{Actual production input}}{\text{Actual production output}} \} .100\% \quad ....(3.24)$$

Planned production time is nothing but the loading time for the job in which total observation time is taken where planned downtime is not considered (i.e. Planned production time = observation time – planned downtime). Planned downtime is the machine setup time, loading & unloading time of equipment during job operation, schedule maintenance time or schedule breaks etc. On the other hand unplanned downtime is simply the minor stoppage time loss, sudden breakdown time loss, idle time, uncertain changeover time loss for loading unloading of material, machine breakdown and its corresponding setup time loss etc. which are directly concerned with the losses related to availability and performance. It is also important to mention that production output is the combination of production input and rework item & scrap.

3.14 Technical Audit

Technical audit is directly concerned with time motion study of the facilities to analyse the performance rate of a production unit. Time and Motion Study have the objective to eliminate work that is not required. Moreover, it provides a method to measure job performance or to determine the production rate for the individual or group work of each section or an entire factory [92]. It helps to eliminate the unnecessary motion, fatigue and improves the method, procedure, technique, and processes related to a job for making effective utilization of materials, machines and human resources. It also improves the layout and design of plant and equipment and working environment in accordance with the individuals. Time-motion study of different facilities of a production unit helps to determine the scheduling and effectiveness of the machines.

Technical Audit is nothing but the intensive study or inspection of different performance rate and risk management process which is derived by the continuous intensive observation over a long time period. It is an intensive inspection of an organization of root cause of system failure also from organization tail to head. In 2012, S.B. Srivastava [33] concluded in his research paper that the Technical Audit will increase the Customer and Owner's DELIGHT and gives a NEW thrust to the organization.

The success of Technical Audit depends upon the implementation of audit report and management's ability to adopt it. The Technical Audit assures the increased knowledge about the Product Quality and Profitability. Standard ISO 19011 provides guidance on auditing of management systems including the principles for auditing, managing an audit programme and conducting the management system audits. Later, ISO 19011:2011 introduces the concept of risk in management system audits but it does not give specific guidance for the risk assessment and risk management process of the organization. But, we can safely proposed that Technical Audit will help to make decisions for the implement of different strategies for the increment of accessibility, productivity, reliability, availability, overall effectively or efficiency etc. Technical Audit will also help to implement & improve the inventory section of a press or any type of plant or organization. As a result, the failure rate is decreased for the better performance rate.

Chapter 4:

DATA COLLECTION

4.1 Introduction

Data collection is essential to maintain the integrity of research. Data collection process is necessary as it ensures that data gathered are both defined and accurate. The subsequent decisions based on arguments embodied in the findings seems to be valid. The entire data for all machines are collected for three month and database is prepared from these data. The database comprises the following:-

- Number of breakdown related to different types of failures and their components.
- Daily available operating hours and breakdown hours for individual components

The data are collected in a manner so that it simulates the entire process of production. The database includes the name of the machines, the detailed information and use of each machine component. It also furnishes the number and time of failures along with its causes.

4.2 Details of the all components and sub-components of the plants

4.2.1 Details of Component 1

Machine name: Printing machine

Machine type: Four colour web-offset printing machine

Year of manufacture: 2009

Name of manufacturer: The Printers House Pvt. Ltd.,India

Model: Orient Xcell, 3c-1

Maximum number of printable colours: 4

Max. Printing area: 700-395 mm

Plate size: 780-510 mm

Present condition: Running

4.2.2 Details of Component 2

Machine name: Computer to coating plate or computer to plate (CTP1)

Machine type: Automatic plate printing

Year of manufacture: 2014

Name of manufacturer: Epson

Model: Epson, Sure Colour T5270 (Ultra Colour XD ink)

Plate size: 780-510 mm

Printing duration / plate: 210 sec

Present condition: Running

4.2.3 Details of Component 3

Machine name: Computer to coating plate or computer to plate (CTP2)

Machine type: Automatic plate printing

Year of manufacture: 2009

Name of manufacturer: Epson

Model: Epson, Sure Colour T5270 (Ultra Colour XD ink)

Plate size: 780-510 mm

Printing duration / plate: 300 sec

Present condition: Running

4.2.4 Details of Sub-Component 1 (subcomponent of CTP1 & CTP2)

Machine name: Exposure Unit

Machine type: Exposing of printing plate

Year of manufacture: 2005

Name of manufacturer: Technova, Proteck, Ecolux-i

Present condition: Running

Plate size: 780-510 mm

4.2.5 Details of Sub-Component 2 (subcomponent of printing machine)

Machine name: Compressor 1

Year of manufacture: 2009

Model: BX-11P

Max final pressure: Bar 7.51

Power: 11 kW

Present condition: Running

4.3 Basic data and calculation of different parameters of different components and sub-component

Basic data collected from the plant are operating hour, breakdown hour and number of failures of different machine. The other parameters as given in Table 4.1 to Table 4.5 are calculated from the basic data. Cumulative failures given in the above Tables are determined by using the following equation 4.1:

$$CF_{i+1} = \frac{F_{i+1}}{\sum_{i=0}^{n} F_i} + F_i \quad ....(4.1)$$

Where, F = no. of failure and n = total no. of failure

4.3.1 Data of Component 1 (Printing machine) for failure analysis

Table 4.1: Data of Component 1

No. of Days	Operating Hour (in Minute)	Breakdown Hour (in Minute)	No. of Failure	Cumulative Failure (CF)			
		(x)	(freq)	y = f(x)	x2	x*y	y2
1	75	10	2	0.394477318	100	3.944773176	0.155612354
2	209	81	9	2.169625247	6561	175.739645	4.70727371
3	356	111	8	3.747534517	12321	415.9763314	14.04401495
4	131	9	2	4.142011834	81	37.27810651	17.15626204
5	71	8	3	4.733727811	64	37.86982249	22.40817899
6	77	22	3	5.325443787	484	117.1597633	28.36035153
7	77	10	2	5.719921105	100	57.19921105	32.71749744
8	76	29	2	6.114398422	841	177.3175542	37.38586806
9	331	131	11	8.284023669	17161	1085.207101	68.62504814
10	302	200	11	10.45364892	40000	2090.729783	109.2787756
11	157	60	5	11.43984221	3600	686.3905325	130.8699898
12	83	24	2	11.83431953	576	284.0236686	140.0511187
13	115	10	2	12.22879684	100	122.2879684	149.5434723
14	75	39	5	13.21499014	1521	515.3846154	174.6359643

15	0	0	0	13.21499014	0	0	174.6359643
16	186	108	16	16.37080868	11664	1768.047337	268.0033768
17	300	100	9	18.14595661	10000	1814.595661	329.2757412
18	147	49	4	18.93491124	2401	927.8106509	358.5308638
19	88	53	5	19.92110454	2809	1055.81854	396.850406
20	85	49	4	20.71005917	2401	1014.792899	428.9065509
21	102	22	4	21.49901381	484	472.9783037	462.2075947
22	78	47	3	22.09072978	2209	1038.2643	488.0003423
23	194	216	12	24.45759369	46656	5282.840237	598.173889
24	204	67	6	25.64102564	4489	1717.948718	657.4621959
25	124	18	3	26.23274162	324	472.1893491	688.1567328
26	86	22	2	26.62721893	484	585.7988166	709.0087882
27	77	13	2	27.02169625	169	351.2820513	730.1720684
28	83	23	4	27.81065089	529	639.6449704	773.4323028
29	18	257	1	28.00788955	66049	7198.027613	784.4418768
30	258	91	11	30.17751479	8281	2746.153846	910.6823991
31	246	139	10	32.14990138	19321	4468.836292	1033.616159
32	164	24	3	32.74161736	576	785.7988166	1072.013507
33	83	12	2	33.13609467	144	397.6331361	1098.00077
34	75	13	2	33.53057199	169	435.8974359	1124.299258
35	77	8	1	33.72781065	64	269.8224852	1137.565211
36	80	5	1	33.92504931	25	169.6252465	1150.908971
37	186	110	8	35.50295858	12100	3905.325444	1260.460068
38	248	130	7	36.88362919	16900	4794.871795	1360.402102
39	150	20	4	37.67258383	400	753.4516765	1419.223572
40	78	7	1	37.86982249	49	265.0887574	1434.123455
41	108	22	4	38.65877712	484	850.4930966	1494.501048
42	75	27	4	39.44773176	729	1065.088757	1556.123541
43	186	65	6	40.63116371	4225	2641.025641	1650.891464
44	175	196	7	42.01183432	38416	8234.319527	1764.994223
45	239	70	9	43.78698225	4900	3065.088757	1917.299814
46	161	31	5	44.77317554	961	1387.968442	2004.637248
47	78	12	2	45.16765286	144	542.0118343	2040.116865
48	286	113	6	46.35108481	12769	5237.672584	2148.423063
49	223	139	9	48.12623274	19321	6689.546351	2316.134278
50	203	45	3	48.71794872	2025	2192.307692	2373.438527
51	310	293	25	53.64891519	85849	15719.13215	2878.206101
52	411	124	14	56.41025641	15376	6994.871795	3182.117028
53	240	34	6	57.59368836	1156	1958.185404	3317.032939
54	83	10	2	57.98816568	100	579.8816568	3362.627359
55	74	16	2	58.382643	256	934.122288	3408.533003
56	255	79	9	60.15779093	6241	4752.465483	3618.959809
57	81	7	1	60.35502959	49	422.4852071	3642.729596
58	257	218	14	63.11637081	47524	13759.36884	3983.676264

59	204	59	5	64.1025641	3481	3782.051282	4109.138725
60	127	33	2	64.49704142	1089	2128.402367	4159.868352
61	147	63	5	65.48323471	3969	4125.443787	4288.054029
62	134	99	13	68.04733728	9801	6736.686391	4630.440111
63	474	78	12	70.41420118	6084	5492.307692	4958.159728
64	682	140	25	75.34516765	19600	10548.32347	5676.894289
65	219	162	24	80.07889546	26244	12972.78107	6412.629499
66	528	140	12	82.44575937	19600	11542.40631	6797.303238
67	75	5	1	82.64299803	25	413.2149901	6829.865123
68	253	43	6	83.82642998	1849	3604.536489	7026.870363
69	331	54	8	85.40433925	2916	4611.83432	7293.901163
70	340	194	17	88.75739645	37636	17218.93491	7877.875425
71	408	97	9	90.53254438	9409	8781.656805	8196.141592
72	168	79	5	91.51873767	6241	7229.980276	8375.679345
73	262	64	5	92.50493097	4096	5920.315582	8557.162253
74	83	11	2	92.89940828	121	1021.893491	8630.30006
75	79	12	2	93.2938856	144	1119.526627	8703.749091
76	86	5	1	93.49112426	25	467.4556213	8740.590315
77	0	0	0	93.49112426	0	0	8740.590315
78	0	0	0	93.49112426	0	0	8740.590315
79	0	0	0	93.49112426	0	0	8740.590315
80	0	0	0	93.49112426	0	0	8740.590315
81	144	29	3	94.08284024	841	2728.402367	8851.580827
82	171	72	6	95.26627219	5184	6859.171598	9075.662617
83	82	65	3	95.85798817	4225	6230.769231	9188.753895
84	95	6	1	96.05522682	36	576.3313609	9226.6066
85	86	6	2	96.44970414	36	578.6982249	9302.545429
86	183	51	6	97.63313609	2601	4979.289941	9532.229264
87	122	93	4	98.42209073	8649	9153.254438	9686.907944
88	89	6	1	98.61932939	36	591.7159763	9725.772129
89	85	13	2	99.01380671	169	1287.179487	9803.733918
90	80	15	2	99.40828402	225	1491.12426	9882.006933
91	79	22	2	99.80276134	484	2195.66075	9960.591171
92	73	11	1	100	121	1100	10000
	N=	Σx =	Σ(freq) =	Σf(x) =	(Σx²) =	Σ(x.f(x)) =	Σf(x²) =
	14886	5575	507	4728.994083	707669	271654.4379	338902.3105

p =	$\Sigma\{x.f(x)\} - [\{\Sigma x*\Sigma f(x)\} / N]$	269883.3683
q =	sqrt of $[(\Sigma x^2) - \{(\Sigma x)^2\}/N]*[\Sigma f(x^2) - \{\Sigma f(x)\}^2/N]$	487917.0629
$R_{x,f(x)}$	= p/q	0.553133696

4.3.2 Data of Component 2 (CTP 1) for failure analysis

Table 4.2: Data of Component 2

No. of Days	**Operating Hour (in Minute)**	**Breakdown Hour (in Minute)**	**No. of Failure**	**Cumulative Failure (CF)**			
		(x)	(freq)	y = f(x)	x2	x*y	y2
1	13	5	3	0.423728814	25	2.118644068	0.179546107
2	16	33	5	1.129943503	1089	37.28813559	1.27677232
3	14	9	3	1.553672316	81	13.98305085	2.413897667
4	42	59	11	3.107344633	3481	183.3333333	9.655590667
5	9	7	4	3.672316384	49	25.70621469	13.48590763
6	10	86	2	3.95480226	7396	340.1129944	15.64046091
7	38	35	9	5.225988701	1225	182.9096045	27.3109579
8	37	59	10	6.638418079	3481	391.6666667	44.06859459
9	45	57	13	8.474576271	3249	483.0508475	71.81844298
10	9	36	2	8.757062147	1296	315.2542373	76.68613744
11	46	43	12	10.4519774	1849	449.4350282	109.2438316
12	13	37	4	11.01694915	1369	407.6271186	121.3731686
13	25	9	5	11.72316384	81	105.5084746	137.4325705
14	36	13	10	13.13559322	169	170.7627119	172.5438093
15	16	9	4	13.70056497	81	123.3050847	187.7054805
16	14	33	4	14.26553672	1089	470.7627119	203.505538
17	17	56	4	14.83050847	3136	830.5084746	219.9439816
18	44	116	11	16.38418079	13456	1900.564972	268.4413802
19	27	40	7	17.37288136	1600	694.9152542	301.8170066
20	30	98	8	18.50282486	9604	1813.276836	342.3545278
21	35	56	9	19.7740113	3136	1107.344633	391.0115229
22	8	5	3	20.19774011	25	100.9887006	407.9487057
23	44	31	12	21.89265537	961	678.6723164	479.288359
24	0	0	0	21.89265537	0	0	479.288359
25	40	79	10	23.30508475	6241	1841.101695	543.126975
26	27	23	7	24.29378531	529	558.7570621	590.1880047
27	20	7	5	25	49	175	625
28	35	67	9	26.27118644	4489	1760.169492	690.175237
29	31	47	8	27.40112994	2209	1287.853107	750.8219222
30	17	24	4	27.96610169	576	671.1864407	782.102844
31	37	51	10	29.37853107	2601	1498.305085	863.098088
32	31	21	8	30.50847458	441	640.6779661	930.767021
33	35	42	10	31.92090395	1764	1340.677966	1018.944109
34	15	20	4	32.48587571	400	649.7175141	1055.33212
35	38	21	11	34.03954802	441	714.8305085	1158.69083
36	23	90	6	34.88700565	8100	3139.830508	1217.103163
37	33	58	9	36.15819209	3364	2097.175141	1307.414855

38	20	57	7	37.14689266	3249	2117.372881	1379.891634
39	32	51	9	38.4180791	2601	1959.322034	1475.948801
40	24	33	7	39.40677966	1089	1300.423729	1552.894283
41	28	52	8	40.53672316	2704	2107.909605	1643.225925
42	26	9	7	41.52542373	81	373.7288136	1724.360816
43	27	33	7	42.51412429	1089	1402.966102	1807.450764
44	27	38	7	43.50282486	1444	1653.107345	1892.495771
45	28	44	7	44.49152542	1936	1957.627119	1979.495835
46	23	6	6	45.33898305	36	272.0338983	2055.623384
47	24	38	7	46.32768362	1444	1760.451977	2146.254269
48	27	34	7	47.31638418	1156	1608.757062	2238.840212
49	27	37	7	48.30508475	1369	1787.288136	2333.381212
50	25	56	5	49.01129944	3136	2744.632768	2402.107472
51	34	66	10	50.42372881	4356	3327.966102	2542.552427
52	17	50	4	50.98870056	2500	2549.435028	2599.847585
53	31	45	9	52.25988701	2025	2351.694915	2731.09579
54	10	96	2	52.54237288	9216	5044.067797	2760.700948
55	30	50	8	53.67231638	2500	2683.615819	2880.717546
56	32	105	9	54.94350282	11025	5769.067797	3018.788503
57	28	94	6	55.79096045	8836	5244.350282	3112.631268
58	45	22	13	57.62711864	484	1267.79661	3320.884803
59	16	112	5	58.33333333	12544	6533.333333	3402.777778
60	27	41	8	59.46327684	1681	2437.99435	3535.881292
61	59	82	17	61.86440678	6724	5072.881356	3827.204826
62	19	5	5	62.57062147	25	312.8531073	3915.082671
63	44	77	12	64.26553672	5929	4948.446328	4130.05921
64	13	3	3	64.68926554	9	194.0677966	4184.701076
65	40	59	11	66.24293785	3481	3908.333333	4388.126815
66	7	1	1	66.38418079	1	66.38418079	4406.859459
67	34	86	9	67.65536723	7396	5818.361582	4577.248715
68	28	57	8	68.78531073	3249	3920.762712	4731.418973
69	24	15	6	69.63276836	225	1044.491525	4848.72243
70	39	63	10	71.04519774	3969	4475.847458	5047.420122
71	95	209	28	75	43681	15675	5625
72	102	117	30	79.23728814	13689	9270.762712	6278.547831
73	13	5	3	79.66101695	25	398.3050847	6345.877621
74	31	75	8	80.79096045	5625	6059.322034	6527.179291
75	23	52	6	81.63841808	2704	4245.19774	6664.831306
76	36	27	11	83.1920904	729	2246.186441	6920.923904
77	15	23	4	83.75706215	529	1926.412429	7015.245459
78	0	0	0	83.75706215	0	0	7015.245459
79	0	0	0	83.75706215	0	0	7015.245459
80	0	0	0	83.75706215	0	0	7015.245459
81	29	85	7	84.74576271	7225	7203.389831	7181.844298

82	36	79	10	86.15819209	6241	6806.497175	7423.234064
83	36	118	10	87.57062147	13924	10333.33333	7668.613744
84	37	42	10	88.98305085	1764	3737.288136	7917.983338
85	28	32	7	89.97175141	1024	2879.096045	8094.916052
86	57	87	15	92.09039548	7569	8011.864407	8480.64094
87	22	27	7	93.07909605	729	2513.135593	8663.718121
88	41	43	12	94.7740113	1849	4075.282486	8982.113218
89	19	49	5	95.48022599	2401	4678.531073	9116.473555
90	44	112	12	97.17514124	12544	10883.61582	9443.008076
91	32	105	9	98.44632768	11025	10336.86441	9691.679434
92	18	30	4	99.01129944	900	2970.338983	9803.237416
93	26	16	7	100	256	1600	10000
	N=	Σx =	Σ(freq) =	Σf(x) =	(Σx^2) =	Σ(x.f(x)) =	$\Sigma f(x^2)$ =
	2625	4432	708	4446.751412	331074	231072.1751	293102.6964
p =	Σ{x.f(x)} - [{Σx*Σf(x)} / N]					223564.3647	
q =	sqrt of [(Σx^2) - $\{(\Sigma x)^2\}$/N]*[$\Sigma f(x^2)$ - $\{\Sigma f(x)\}^2$/N]					303986.6377	
$R_{x,f(x)}$	= p/q					0.735441421	

4.3.3 Data of Component 3 (CTP 2) for failure analysis

Table 4.3: Data of Component 3

No. of Days	**Operating Hour (in Minute)**	**Breakdown Hour (in Minute)**	**No. of Failure**	**Cumulative Failure (CF)**			
		(x)	(freq)	y = f(x)	x2	x*y	y2
1	5	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	10	3	1	0.421940928	9	1.265822785	0.178034147
4	40	29	5	2.53164557	841	73.41772152	6.40922929
5	5	65	1	2.953586498	4225	191.9831224	8.723673201
6	25	84	4	4.641350211	7056	389.8734177	21.54213178
7	28	6	4	6.329113924	36	37.97468354	40.05768306
8	0	0	0	6.329113924	0	0	40.05768306
9	10	60	2	7.172995781	3600	430.3797468	51.45186847
10	10	1	1	7.594936709	1	7.594936709	57.68306361
11	21	135	2	8.438818565	18225	1139.240506	71.21365878
12	10	25	1	8.860759494	625	221.5189873	78.5130588
13	10	69	1	9.282700422	4761	640.5063291	86.16852712
14	15	0	1	9.70464135	0	0	94.18006374
15	16	9	4	11.39240506	81	102.5316456	129.7868931
16	25	25	4	13.08016878	625	327.0042194	171.0908152

17	0	0	0	13.08016878	0	0	171.0908152
18	15	15	4	14.76793249	225	221.5189873	218.09183
19	15	120	2	15.61181435	14400	1873.417722	243.7287472
20	11	0	0	15.61181435	0	0	243.7287472
21	97	59	8	18.98734177	3481	1120.253165	360.5191476
22	20	1	2	19.83122363	1	19.83122363	393.2774306
23	50	51	12	24.89451477	2601	1269.620253	619.7368655
24	35	125	6	27.42616034	15625	3428.270042	752.1942709
25	23	2	3	28.69198312	4	57.38396624	823.2298955
26	5	60	1	29.11392405	3600	1746.835443	847.6205736
27	10	41	1	29.53586498	1681	1210.970464	872.3673201
28	11	0	0	29.53586498	0	0	872.3673201
29	5	70	1	29.95780591	4900	2097.046414	897.4701348
30	31	60	5	32.06751055	3600	1924.050633	1028.325233
31	6	0	0	32.06751055	0	0	1028.325233
32	36	36	7	35.02109705	1296	1260.759494	1226.477238
33	0	0	0	35.02109705	0	0	1226.477238
34	20	89	5	37.13080169	7921	3304.64135	1378.696434
35	5	0	0	37.13080169	0	0	1378.696434
36	30	35	7	40.08438819	1225	1402.953586	1606.758176
37	86	86	16	46.83544304	7396	4027.848101	2193.558725
38	20	6	3	48.10126582	36	288.6075949	2313.731774
39	36	65	6	50.63291139	4225	3291.139241	2563.691716
40	10	0	0	50.63291139	0	0	2563.691716
41	5	65	1	51.05485232	4225	3318.565401	2606.597945
42	13	48	1	51.47679325	2304	2470.886076	2649.860243
43	11	27	1	51.89873418	729	1401.265823	2693.478609
44	15	8	2	52.74261603	64	421.9409283	2781.783546
45	45	90	8	56.11814346	8100	5050.632911	3149.246025
46	21	57	1	56.54008439	3249	3222.78481	3196.781143
47	6	39	1	56.96202532	1521	2221.518987	3244.672328
48	10	30	1	57.38396624	900	1721.518987	3292.919582
49	20	86	3	58.64978903	7396	5043.881857	3439.797753
50	24	41	3	59.91561181	1681	2456.540084	3589.880539
51	25	103	5	62.02531646	10609	6388.607595	3847.139881
52	10	63	1	62.44725738	3969	3934.177215	3899.659955
53	20	13	3	63.71308017	169	828.2700422	4059.356585
54	25	11	3	64.97890295	121	714.7679325	4222.257829
55	10	34	2	65.82278481	1156	2237.974684	4332.639
56	20	98	3	67.08860759	9604	6574.683544	4500.881269
57	30	121	5	69.19831224	14641	8372.995781	4788.406416
58	45	42	8	72.57383966	1764	3048.101266	5266.962203
59	45	14	9	76.37130802	196	1069.198312	5832.576688
60	5	0	0	76.37130802	0	0	5832.576688

61	0	0	0	76.37130802	0	0	5832.576688
62	5	57	1	76.79324895	3249	4377.21519	5897.203084
63	5	0	0	76.79324895	0	0	5897.203084
64	15	49	3	78.05907173	2401	3824.894515	6093.218679
65	47	16	8	81.43459916	256	1302.953586	6631.59394
66	11	30	1	81.85654008	900	2455.696203	6700.493155
67	15	5	3	83.12236287	25	415.6118143	6909.327209
68	50	36	5	85.23206751	1296	3068.35443	7264.505332
69	10	0	0	85.23206751	0	0	7264.505332
70	5	52	0	85.23206751	2704	4432.067511	7264.505332
71	10	51	1	85.65400844	2601	4368.35443	7336.609162
72	40	205	7	88.60759494	42025	18164.55696	7851.30588
73	40	60	7	91.56118143	3600	5493.670886	8383.449946
74	15	10	2	92.40506329	100	924.0506329	8538.695722
75	0	0	0	92.40506329	0	0	8538.695722
76	0	0	0	92.40506329	0	0	8538.695722
77	0	0	0	92.40506329	0	0	8538.695722
78	0	0	0	92.40506329	0	0	8538.695722
79	0	0	0	92.40506329	0	0	8538.695722
80	0	0	0	92.40506329	0	0	8538.695722
81	5	0	0	92.40506329	0	0	8538.695722
82	25	101	5	94.51476793	10201	9545.991561	8933.041357
83	10	0	0	94.51476793	0	0	8933.041357
84	30	19	5	96.62447257	361	1835.864979	9336.2887
85	5	0	0	96.62447257	0	0	9336.2887
86	20	67	4	98.31223629	4489	6586.919831	9665.295804
87	10	0	0	98.31223629	0	0	9665.295804
88	20	110	3	99.57805907	12100	10953.5865	9915.789848
89	0	0	0	99.57805907	0	0	9915.789848
90	5	0	0	99.57805907	0	0	9915.789848
91	0	0	0	99.57805907	0	0	9915.789848
92	10	94	1	100	8836	9400	10000
93	5	0	0	100	0	0	10000
	N=	Σx =	Σ(freq) =	Σf(x) =	(Σx^2) =	Σ(x.f(x)) =	$\Sigma f(x^2)$ =
	1625	3384	237	5066.244726	279844	179756.5401	377076.8573

p =	Σ{x.f(x)} - [{Σx*Σf(x)} / N]	169206.2803
q =	sqrt of [(Σx^2) - $\{(\Sigma x)^2\}$/N]*[$\Sigma f(x^2)$ - $\{\Sigma f(x)\}^2$/N]	313937.2476
$R_{x,f(x)}$	= p/q	0.538981219

4.3.4 Data of Sub-Component 1 (Exposure unit) for failure analysis

Table 4.4: Data of sub-component 1

No. of Days	**Operating Hour (in Minute)**	**Breakdown Hour (in Minute)** (x)	**No. of Failure** (freq)	**Cumulative Failure (CF)** y = f(x)	x2	x*y	y2
1	10	81	5	0.422654269	6561	34.23499577	0.178636631
2	20	52	9	1.183431953	2704	61.53846154	1.400511187
3	10	12	4	1.521555368	144	18.25866441	2.315130737
4	40	69	18	3.043110735	4761	209.9746407	9.260522948
5	6	30	3	3.296703297	900	98.9010989	10.86825263
6	18	72	8	3.972950127	5184	286.0524091	15.78433271
7	24	46	11	4.902789518	2116	225.5283178	24.03734506
8	21	70	9	5.663567202	4900	396.4497041	32.07599345
9	34	93	16	7.016060862	8649	652.4936602	49.22511002
10	16	43	7	7.607776839	1849	327.1344041	57.87826843
11	36	71	18	9.129332206	5041	648.1825866	83.34470653
12	12	28	5	9.551986475	784	267.4556213	91.24044562
13	30	195	13	10.65088757	38025	2076.923077	113.4414061
14	20	58	9	11.41166526	3364	661.876585	130.226104
15	10	14	4	11.74978867	196	164.4970414	138.0575339
16	20	96	9	12.51056636	9216	1201.01437	156.5142706
17	12	60	5	12.93322063	3600	775.9932375	167.2681957
18	36	81	15	14.20118343	6561	1150.295858	201.6736109
19	22	85	10	15.04649197	7225	1278.951817	226.3969206
20	22	17	9	15.80726965	289	268.7235841	249.8697739
21	24	67	11	16.73710904	4489	1121.386306	280.1308192
22	14	60	6	17.24429417	3600	1034.65765	297.3656813
23	40	88	19	18.85038039	7744	1658.833474	355.3368408
24	16	85	6	19.35756551	7225	1645.393068	374.7153425
25	28	93	13	20.45646661	8649	1902.451395	418.4670262
26	18	41	8	21.13271344	1681	866.4412511	446.5915774
27	16	12	7	21.72442942	144	260.693153	471.9508335
28	24	77	11	22.65426881	5929	1744.378698	513.2158952
29	16	51	7	23.24598478	2601	1185.545224	540.3758086
30	26	62	12	24.26035503	3844	1504.142012	588.5648262
31	22	62	10	25.10566357	3844	1556.551141	630.2943431
32	24	48	11	26.03550296	2304	1249.704142	677.8474143
33	24	96	11	26.96534235	9216	2588.672866	727.1296881
34	10	54	4	27.30346577	2916	1474.387151	745.4792428
35	24	27	11	28.23330516	729	762.2992392	797.1195201
36	20	55	9	28.99408284	3025	1594.674556	840.6568397
37	36	132	17	30.43110735	17424	4016.906171	926.0522948

38	34	89	16	31.78360101	7921	2828.74049	1010.197293
39	26	56	12	32.79797126	3136	1836.686391	1075.706919
40	20	73	9	33.55874894	5329	2449.788673	1126.189631
41	20	89	9	34.31952663	7921	3054.43787	1177.829908
42	18	34	8	34.99577346	1156	1189.856298	1224.70416
43	18	36	8	35.67202029	1296	1284.19273	1272.493031
44	22	94	10	36.51732883	8836	3432.62891	1333.515305
45	46	102	21	38.29247675	10404	3905.832629	1466.313776
46	34	139	16	39.64497041	19321	5510.650888	1571.723679
47	10	19	4	39.98309383	361	759.6787828	1598.647792
48	30	51	13	41.08199493	2601	2095.181741	1687.730307
49	28	47	12	42.09636517	2209	1978.529163	1772.103961
50	20	88	8	42.772612	7744	3763.989856	1829.496338
51	57	116	27	45.05494505	13456	5226.373626	2029.948074
52	34	85	14	46.23837701	7225	3930.262046	2137.987508
53	30	66	14	47.42180896	4356	3129.839391	2248.827965
54	14	121	6	47.92899408	14641	5799.408284	2297.188474
55	20	64	9	48.68977177	4096	3116.145393	2370.693875
56	30	134	14	49.87320372	17956	6683.009298	2487.336449
57	28	118	12	50.88757396	13924	6004.733728	2589.545184
58	121	47	47	54.86052409	2209	2578.444632	3009.677104
59	34	109	16	56.21301775	11881	6127.218935	3159.903365
60	18	48	8	56.88926458	2304	2730.6847	3236.388425
61	36	104	17	58.3262891	10816	6065.934066	3401.956
62	68	83	34	61.20033812	6889	5079.628064	3745.481386
63	58	75	27	63.48267117	5625	4761.200338	4030.04954
64	48	44	22	65.34234996	1936	2875.063398	4269.622698
65	60	50	24	67.37109045	2500	3368.554522	4538.863828
66	52	87	24	69.39983094	7569	6037.785292	4816.336534
67	26	92	12	70.41420118	8464	6478.106509	4958.159728
68	36	83	16	71.76669484	6889	5956.635672	5150.458489
69	78	151	37	74.89433643	22801	11309.0448	5609.16163
70	82	91	38	78.10650888	8281	7107.692308	6100.626729
71	62	217	29	80.55790363	47089	17481.06509	6489.575838
72	86	148	41	84.02366864	21904	12435.50296	7059.976892
73	24	96	12	85.03803888	9216	8163.651733	7231.468057
74	28	110	13	86.13693998	12100	9475.063398	7419.57243
75	16	71	7	86.72865596	5041	6157.734573	7521.859765
76	22	30	10	87.5739645	900	2627.218935	7669.199258
77	12	34	5	87.99661877	1156	2991.885038	7743.404914
78	0	0	0	87.99661877	0	0	7743.404914
79	0	0	0	87.99661877	0	0	7743.404914
80	0	0	0	87.99661877	0	0	7743.404914
81	14	93	7	88.58833474	8649	8238.715131	7847.893052

82	32	125	15	89.85629755	15625	11232.03719	8074.154209
83	28	129	13	90.95519865	16641	11733.22063	8272.848161
84	37	103	16	92.30769231	10609	9507.692308	8520.710059
85	18	65	8	92.98393914	4225	6043.956044	8646.012938
86	40	99	19	94.59002536	9801	9364.412511	8947.272897
87	20	60	9	95.35080304	3600	5721.048183	9091.775641
88	32	66	14	96.534235	4356	6371.25951	9318.858526
89	14	66	6	97.04142012	4356	6404.733728	9417.037219
90	28	116	13	98.14032122	13456	11384.27726	9631.522649
91	20	131	9	98.9010989	17161	12956.04396	9781.427364
92	14	59	5	99.32375317	3481	5860.101437	9865.207944
93	18	31	8	100	961	3100	10000
	N=	Σx =	Σ(freq) =	Σf(x) =	(Σx²) =	Σ(x.f(x)) =	Σf(x²) =
	2622	6917	1183	4324.429417	653252	342642.9417	293507.0301
p =	Σ{x.f(x)} - [{Σx*Σf(x)} / N]					331234.8264	
q =	sqrt of [(Σx²) - {(Σx)²}/N]*[Σf(x²) - {Σf(x)}²/N]					426437.917	
$R_{x,f(x)}$	= p/q					0.776748064	

4.3.5 Data of Sub-Component 2 (Compressor) for failure analysis

Table 4.5: Data of sub-component 2

No. of Days	**Operating Hour (in Minute)**	**Breakdown Hour (in Minute)**	**No. of Failure**	**Cumulative Failure (CF)**			
		(x)	(freq)	y = f(x)	x2	x*y	y2
1							
2	180	0	0	0	0	0	0
3	454	0	0	0	0	0	0
4	670	0	0	0	0	0	0
5	185	0	0	0	0	0	0
6	185	0	0	0	0	0	0
7	285	0	0	0	0	0	0
8	222	0	0	0	0	0	0
9	232	0	0	0	0	0	0
10	530	0	0	0	0	0	0
11	10	87	**1**	25	7569	2175	625
12	292	0	0	25	0	0	625
13	235	0	0	25	0	0	625
14	249	0	0	25	0	0	625
15	200	0	0	25	0	0	625
16	15	0	0	25	0	0	625

17	450	0	0	25	0	0	625
18	634	0	0	25	0	0	625
19	310	0	0	25	0	0	625
20	240	0	0	25	0	0	625
21	230	0	0	25	0	0	625
22	225	0	0	25	0	0	625
23	240	0	0	25	0	0	625
24	460	0	0	25	0	0	625
25	470	0	0	25	0	0	625
26	264	0	0	25	0	0	625
27	240	0	0	25	0	0	625
28	240	0	0	25	0	0	625
29	200	0	0	25	0	0	625
30	93	0	0	25	0	0	625
31	524	0	0	25	0	0	625
32	487	0	0	25	0	0	625
33	275	0	0	25	0	0	625
34	230	0	0	25	0	0	625
35	290	0	0	25	0	0	625
36	210	0	0	25	0	0	625
37	240	0	0	25	0	0	625
38	450	0	0	25	0	0	625
39	420	0	0	25	0	0	625
40	255	0	0	25	0	0	625
41	185	0	0	25	0	0	625
42	238	0	0	25	0	0	625
43	185	0	0	25	0	0	625
44	202	0	0	25	0	0	625
45	437	0	0	25	0	0	625
46	240	0	0	25	0	0	625
47	270	0	0	25	0	0	625
48	179	0	0	25	0	0	625
49	560	0	0	25	0	0	625
50	475	0	0	25	0	0	625
51	571	74	**1**	50	5476	3700	2500
52	595	0	0	50	0	0	2500
53	787	0	0	50	0	0	2500
54	490	0	0	50	0	0	2500
55	2	10	**1**	75	100	750	5625
56	2	210	**1**	100	44100	21000	10000
57	570	0	0	100	0	0	10000
58	216	0	0	100	0	0	10000
59	612	0	0	100	0	0	10000
60	480	0	0	100	0	0	10000

61	262	0	0	100	0	0	10000
62	423	0	0	100	0	0	10000
63	320	0	0	100	0	0	10000
64	760	0	0	100	0	0	10000
65	1021	0	0	100	0	0	10000
66	521	0	0	100	0	0	10000
67	843	0	0	100	0	0	10000
68	220	0	0	100	0	0	10000
69	525	0	0	100	0	0	10000
70	633	0	0	100	0	0	10000
71	865	0	0	100	0	0	10000
72	690	0	0	100	0	0	10000
73	415	0	0	100	0	0	10000
74	636	0	0	100	0	0	10000
75	216	0	0	100	0	0	10000
76	200	0	0	100	0	0	10000
77	204	0	0	100	0	0	10000
78	0	0	0	100	0	0	10000
79	0	0	0	100	0	0	10000
80	0	0	0	100	0	0	10000
81	0	0	0	100	0	0	10000
82	283	0	0	100	0	0	10000
83	295	0	0	100	0	0	10000
84	263	0	0	100	0	0	10000
85	285	0	0	100	0	0	10000
86	203	0	0	100	0	0	10000
87	411	0	0	100	0	0	10000
88	232	0	0	100	0	0	10000
89	210	0	0	100	0	0	10000
90	240	0	0	100	0	0	10000
91	206	0	0	100	0	0	10000
92	195	0	0	100	0	0	10000
93	195	0	0	100	0	0	10000
	N=	Σx =	Σ(freq) =	Σf(x) =	(Σx²) =	Σ(x.f(x)) =	Σf(x²) =
	30689	381	4	5075	57245	27625	420625

p =	Σ{x.f(x)} - [{Σx*Σf(x)} / N]	27561.99453
q =	sqrt of [(Σx²) - {(Σx)²}/N]*[Σf(x²) - {Σf(x)}²/N]	155011.7733
$R_{x,f(x)}$	= p/q	0.177805814

4.3.6 Data collection for Time-Motion Study (TMS)

Data are also collected for study of the time-motion of each component & subcomponent. For Time-Motion study mainly running time of each machine has been observed on hourly basis for a particular day over a period of one month. Also, the corresponding speed & output (in terms of number of impression) has been taken. Though data collection for Time-Motion study has been conducted over a period of one month, for lack of the space only the data for a single day i.e. 1^{st} day has been given for each component and subcomponent from Table 4.6 to Table 4.10 for ready reference.

Table 4.6: TMS Data of component 1

Day 01

Time	M/C running or not	Running Time (min)	Speed (i.p.h)			Output / No. of impression
			min	max	mean	
00:00-1:00	Running	3	31900	32100	32000	1631
01.00-02.00	Running	40	32000	32100	32050	21556
02.00-03:00	Running	32	32000	32000	32000	18766
03.00-04:00	NR					
04.00-05:00	NR					
05:00-06:00	NR					
06:00-07:00	NR					
07:00-08:00	NR					
08:00-09:00	NR					
09:00-10:00	NR					
10:00-11:00	NR					
11:00-12:00	NR					
12:00-13:00	NR					
13:00-14:00	NR					
14:00-15:00	NR					
15:00-16:00	NR					
16:00-17:00	NR					
17:00-18:00	NR					
18:00-19:00	NR					
19:00-20:00	NR					
20:00-21:00	NR					
21:00-22:00	NR					
22:00-23:00	NR					
23:00-00:00	NR					

Table 4.7: TMS Data of component 2

Day 01				**COMP 2**	**CTP1**	
Time	**M/C running or not**	**Running Time (min)**	**Speed (i.p.h)**			**Output / No. of impression**
			min	**max**	**mean**	
00:00-1:00	NR					
01.00-02.00	NR					
02.00-03:00	NR					
03.00-04:00	NR					
04.00-05:00	NR					
05:00-06:00	NR					
06:00-07:00	NR					
07:00-08:00	NR					
08:00-09:00	NR					
09:00-10:00	NR					
10:00-11:00	NR					
11:00-12:00	NR					
12:00-13:00	NR					
13:00-14:00	NR					
14:00-15:00	NR					
15:00-16:00	NR					
16:00-17:00	NR					
17:00-18:00	NR					
18:00-19:00	NR					
19:00-20:00	NR					
20:00-21:00	NR					
21:00-22:00	NR					
22:00-23:00	NR					
23:00-00:00	Running	13	3	4	3.5	4

Table 4.8: TMS Data of component 3

Day 01			**COMP 3**		**CTP 2**	
Time	**M/C running or not**	**Running Time (min)**	**Speed (i.p.h)**			**Output / No. of impression**
			min	**max**	**mean**	
00:00-1:00	NR					
01.00-02.00	NR					
02.00-03:00	NR					
03.00-04:00	NR					
04.00-05:00	NR					
05:00-06:00	NR					
06:00-07:00	NR					
07:00-08:00	NR					
08:00-09:00	NR					
09:00-10:00	NR					
10:00-11:00	NR					
11:00-12:00	NR					
12:00-13:00	NR					
13:00-14:00	NR					
14:00-15:00	NR					
15:00-16:00	NR					
16:00-17:00	NR					
17:00-18:00	NR					
18:00-19:00	NR					
19:00-20:00	NR					
20:00-21:00	NR					
21:00-22:00	NR					
22:00-23:00	Running	5	5	5	5	1
23:00-00:00	NR					

Table 4.9: TMS Data of sub-component 1

Day 01	**EXPOSURE UNIT**	**SUB COMP 1**				
Time	**M/C running or not**	**Running Time (in minute)**	**Speed (i.p.h) min**	**max**	**mean**	**Output / No. of impression**
00:00-1:00	NR					
01.00-02.00	NR					
02.00-03:00	NR					
03.00-04:00	NR					
04.00-05:00	NR					
05:00-06:00	NR					
06:00-07:00	NR					
07:00-08:00	NR					
08:00-09:00	NR					
09:00-10:00	NR					
10:00-11:00	NR					
11:00-12:00	NR					
12:00-13:00	NR					
13:00-14:00	NR					
14:00-15:00	NR					
15:00-16:00	NR					
16:00-17:00	NR					
17:00-18:00	NR					
18:00-19:00	NR					
19:00-20:00	NR					
20:00-21:00	NR					
21:00-22:00	NR					
22:00-23:00	Running	2	2	2	2	1
23:00-00:00	Running	8	2	2	2	4

Table 4.10: TMS Data of sub-component 2

Day 01		SUB COMP 2				Compressor 1
Time	M/C running or not	Running Time (min)	Speed (i.p.h)			Output / No. of impression
			min	max	mean	
00:00-1:00	-					
01.00-02.00	-					
02.00-03:00	-					
03.00-04:00	-					
04.00-05:00	NR					
05:00-06:00	NR					
06:00-07:00	NR					
07:00-08:00	NR					
08:00-09:00	NR					
09:00-10:00	NR					
10:00-11:00	NR					
11:00-12:00	NR					
12:00-13:00	NR					
13:00-14:00	NR					
14:00-15:00	NR					
15:00-16:00	NR					
16:00-17:00	NR					
17:00-18:00	NR					
18:00-19:00	NR					
19:00-20:00	NR					
20:00-21:00	NR					
21:00-22:00	NR					
22:00-23:00	NR					
23:00-00:00	NR					

Chapter 5

DATA ANALYSIS

5.1 Introduction

In this chapter a brief analysis of different components has been carried out by using Reliability Availability Maintainability (RAM) analysis, Risk-based Maintenance (RBM) strategy and the technique of Total Productive Maintenance (TPM). The risk factor of the components and their analysis also have been done by prioritizing the risk.

5.2 Normal scatter plot of failure of different components and sub-components

The basic idea of failure distribution comes from normal scatter plot of failure scenario. The normal scatter plots of different components and sub-components are shown in Figure 5.1 to Figure 5.5 to understand the actual scenario of breakdown.

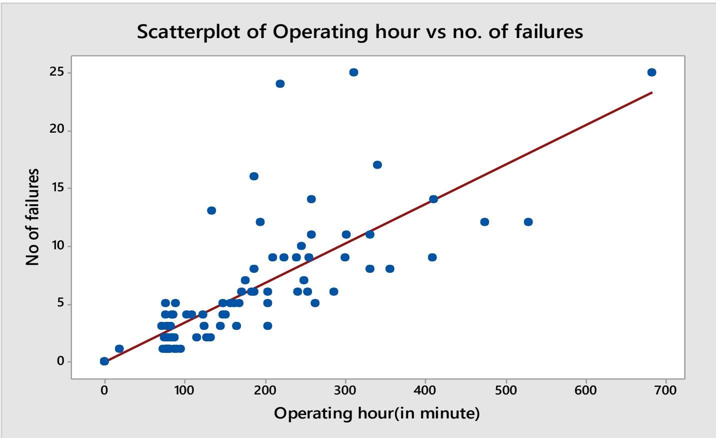


Figure 5.1: Normal scatter plot of operating time Vs. no failure for Component 1 (Printing machine)

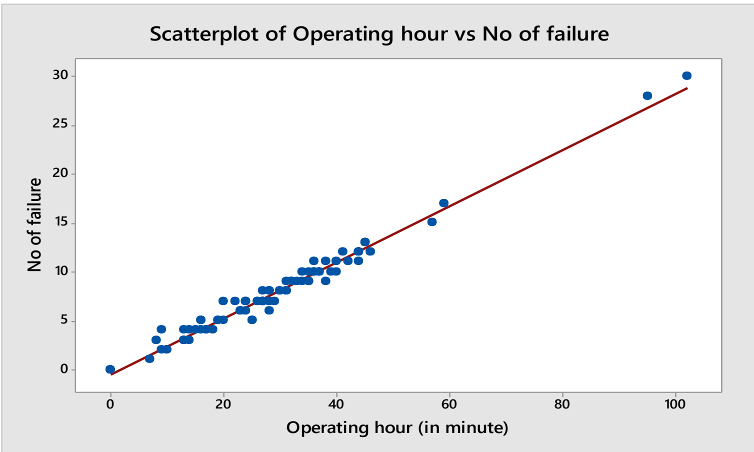


Figure 5.2: Normal scatter plot of operating time Vs. no failure for Component 2 (CTP 1)

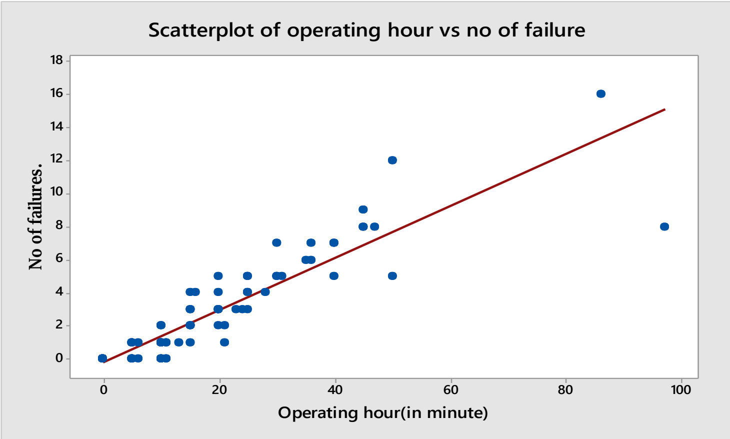


Figure 5.3: Normal scatter plot of operating time Vs. no failure for Component 3 (CTP 2)

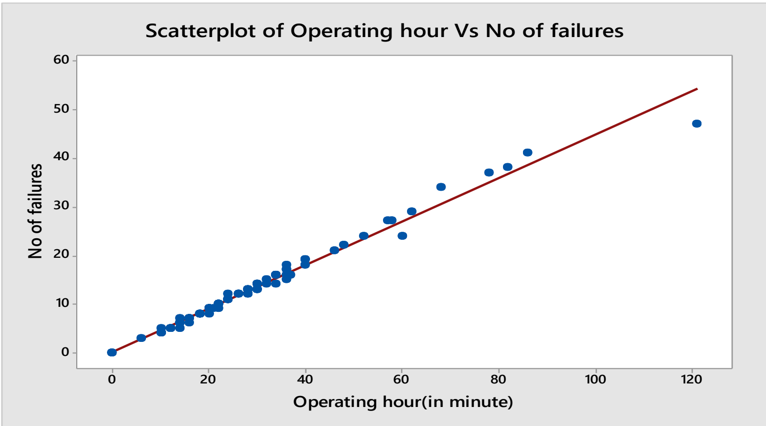


Figure 5.4: Normal scatter plot of operating time Vs. no failure for Sub-component 1 (Exposure unit)

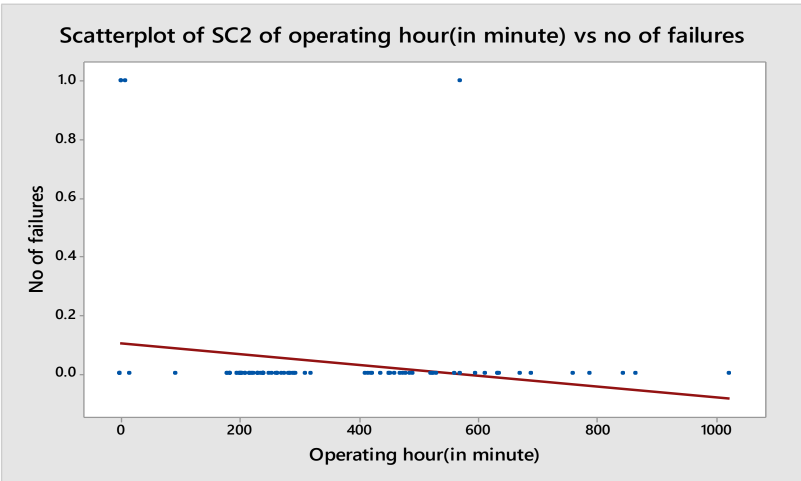


Figure 5.5: Normal scatter plot of operating time Vs. no failure for Sub-component 2 (Compressor)

5.3 Anderson-Darling analysis of different components & sub-components

This test is named after Theodore Wilbur Anderson & Donald A. Darling who invented it in 1952. It is a statistical test of a given sample data that are drawn from a given Probability distribution. If the AD test value (Goodness of fit) is low then the estimated points are fitted nearly and appropriately to the regression line and gives a specific pattern of that set of data. In addition to its use as a test of fit for distributions, it can be used in parameter estimation as the basis for a form of minimum distance estimation procedure. Statistical software 'Minitab17' is used to draw the probability plot. Figure 5.6-5.10 show the probability plot for different components and subcomponents. The different AD test values are also given below in Table 5.1 to Table 5.5.

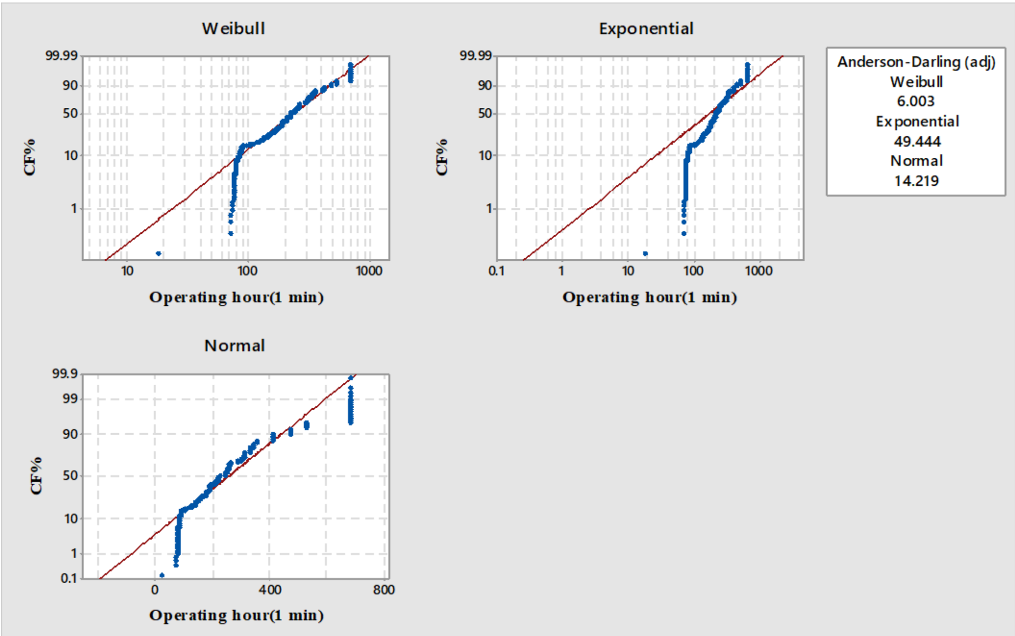


Figure 5.6: Probability Plot of C1 (Printing machine) deriving AD value obtained from Minitab17

Table 5.1: Table of Anderson-Darling test value estimated from Minitab17

Distribution	Goodness-of-Fit Anderson-Darling
Weibull	6.003
Exponential	49.444
Normal	14.219

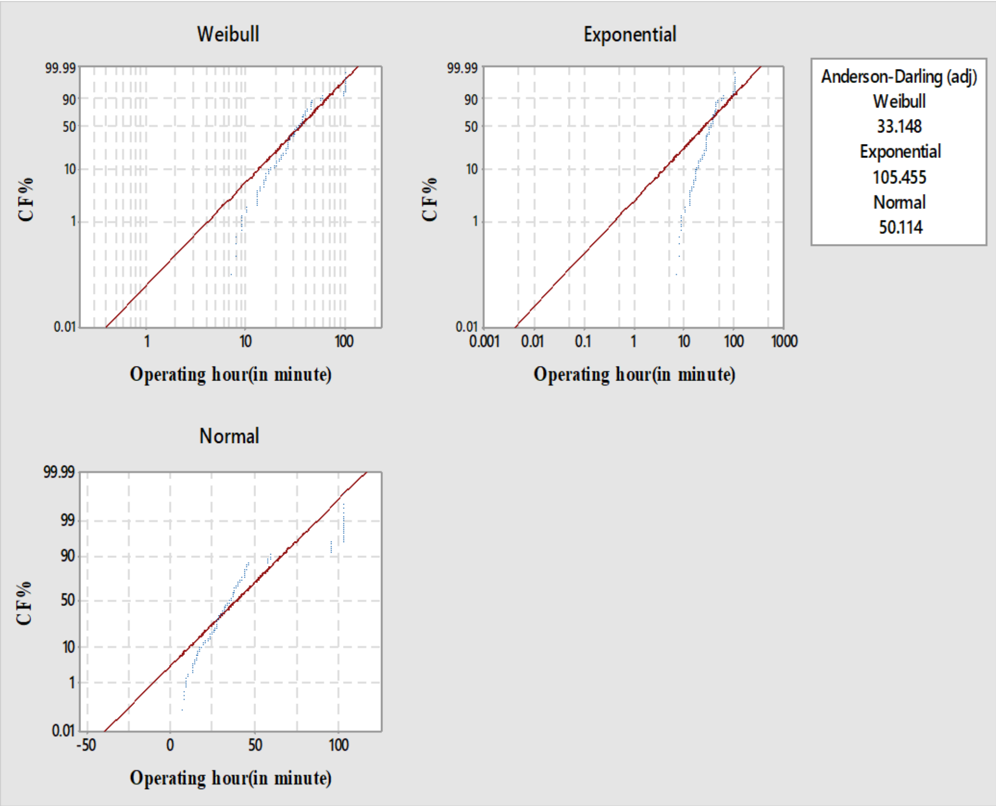


Figure 5.7: Probability Plot of C2 (CTP1) deriving AD value obtained from Minitab17

Table 5.2: Table of Anderson-Darling test value estimated from Minitab17

Distribution	Goodness-of-Fit Anderson-Darling
Weibull	33.148
Exponential	105.455
Normal	50114

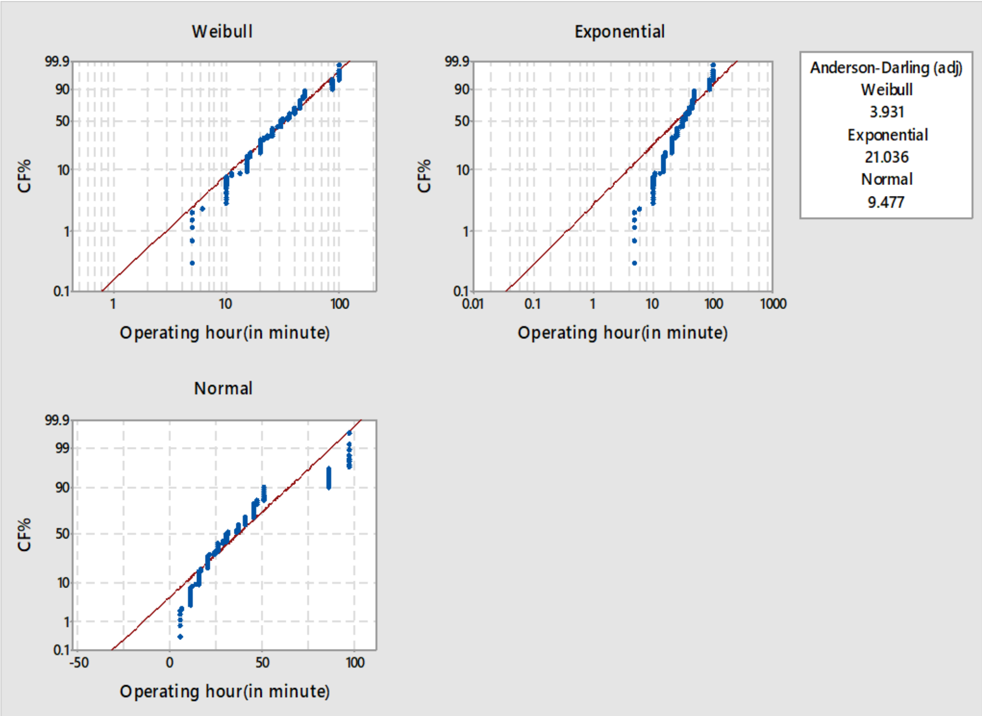


Figure 5.8: Probability Plot of C3 (CTP2) deriving AD value obtained from Minitab17

Table 5.3: Table of Anderson-Darling test value estimated from Minitab17

Distribution	Goodness-of-Fit Anderson-Darling
Weibull	3.931
Exponential	21.036
Normal	9.477

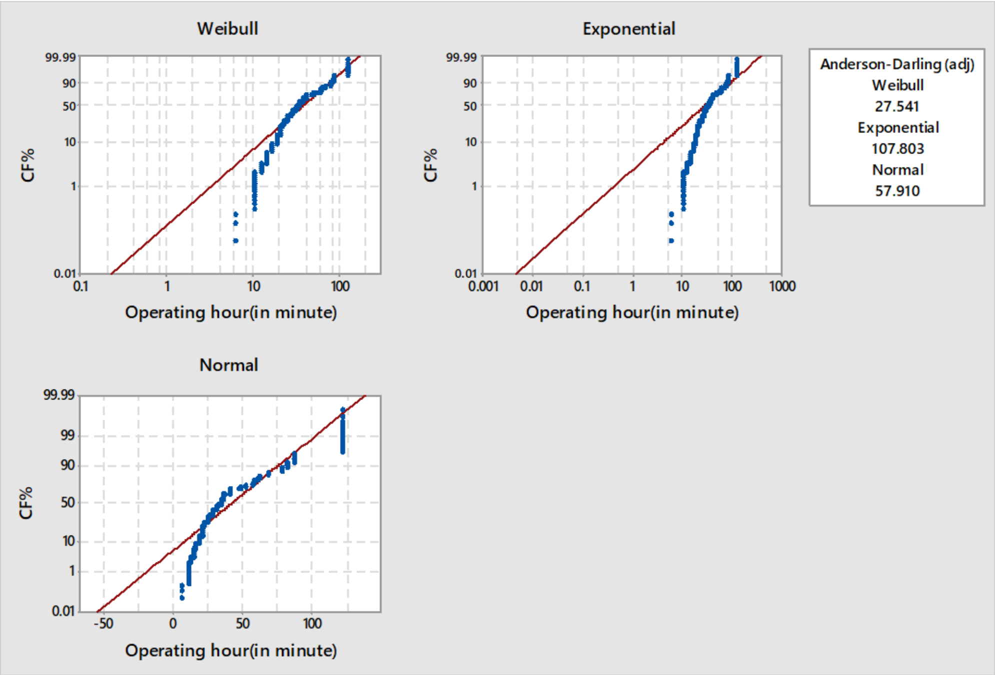


Figure 5.9: Probability Plot of SC1 (Exposure Unit) deriving AD value obtained from Minitab17

Table 5.4: Table of Anderson-Darling test value estimated from Minitab17

Distribution	Goodness-of-Fit Anderson-Darling
Weibull	27.541
Exponential	107.803
Normal	57.910

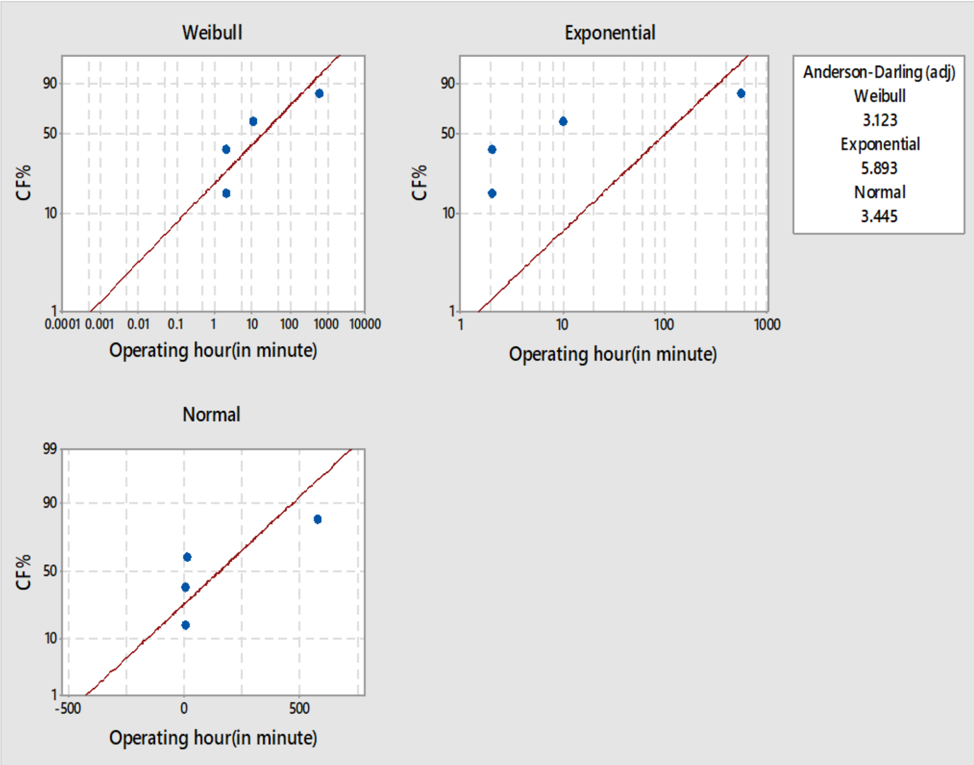


Figure 5.10: Probability Plot of SC2 (Compressor) deriving AD value obtained from Minitab17

Table 5.5: Table of Anderson-Darling test value estimated from Minitab17

Distribution	Goodness-of-Fit Anderson-Darling
Weibull	3.123
Exponential	5.893
Normal	3.445

5.4 Weibull plot

It has been observed from Table 4.1 to Table 4.5 that the values of correlation coefficient of breakdown for all the component are not constant but it is either increasing or decreasing. Hence Weibull distribution was applied in this case. It is used in life data analysis. Depending on the values of the parameters the Weibull distribution can be used to model a variety of life behaviour. To plot the Weibull distribution, statistical software 'MINITAB 17" is used. MINITAB 17 is used to plot several distributions like normal, exponential & Weibull. An important aspect of the Weibull distribution is how the values of the shape parameter (β) and scale parameter (Ƞ) affects such distribution characteristics. Here 'β' determines the shape of the distribution. If 'β' is greater than 1 then the failure is increasing and also indicates that it is failing due to ageing. If β is equals to 1 then the failure rate is constant over time. If β is less than 1 then the failure rate is decreasing over time and it indicates that the machine is failing before time or early failure. The three lines in Weibull plot indicate lower bound, average and upper bounds of operating hour. Moreover, the reliability software "EASYFIT" can be used to develop cumulative distribution function (CDF) of failure rate, survival analysis and the estimation of different parameters

5.4.1 Weibull plot of component 1

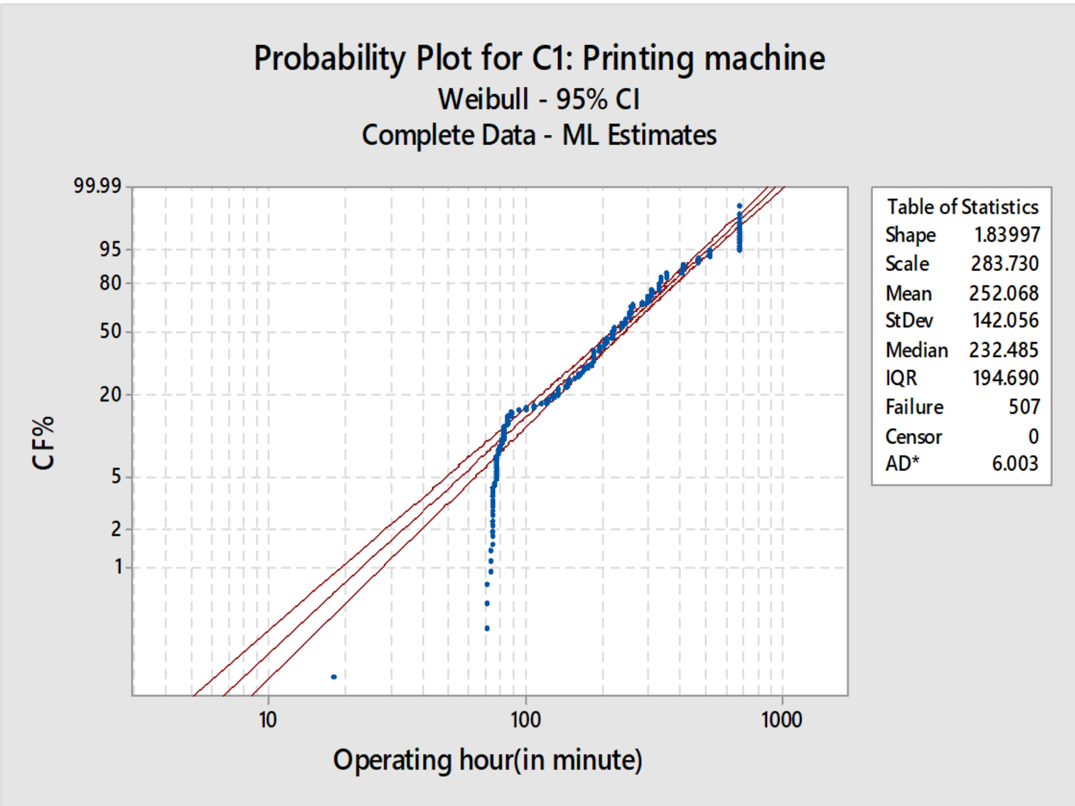
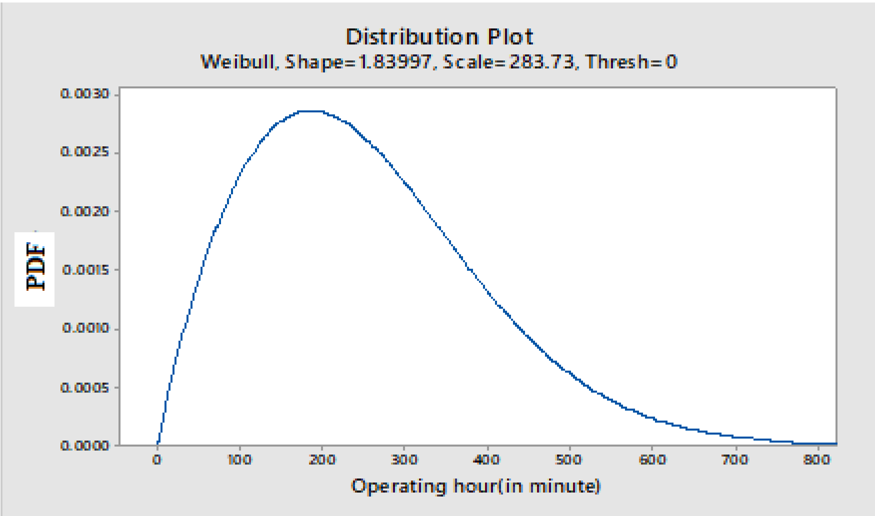
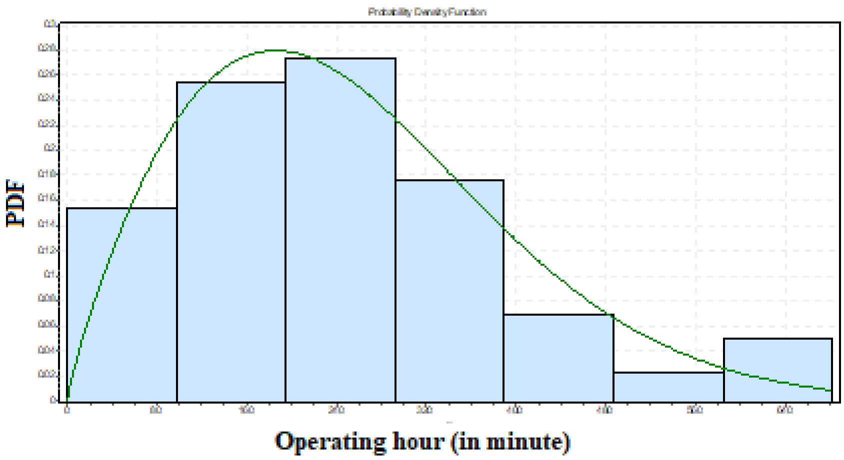


Figure 5.11: Weibull plot of component 1 obtained from Minitab17

Figure 5.11 shows Weibull plot for regression analysis of component 1 (C1) i.e. printing machine. It also shows the value of Shape & scale parameter i.e. (β = 1.83997 & Ƞ = 283.73) which is estimated by Minitab17.



(a)



(b)

Figure 5.12: PDF distribution of C1: (a) obtained from Minitab17 & (b) obtained from Easyfit

Figures 5.12 (a) & (b) show the distribution of probability density function that describes the failure characteristics of the component 1 by using softwares Minitab17 and Easyfit respectively. Figure 5.13 shows the cumulative distribution function (CDF) of failure rate i.e. reliability and Figure 5.14 shows the survival function for survival analysis (which is described later in Art. 5.5).

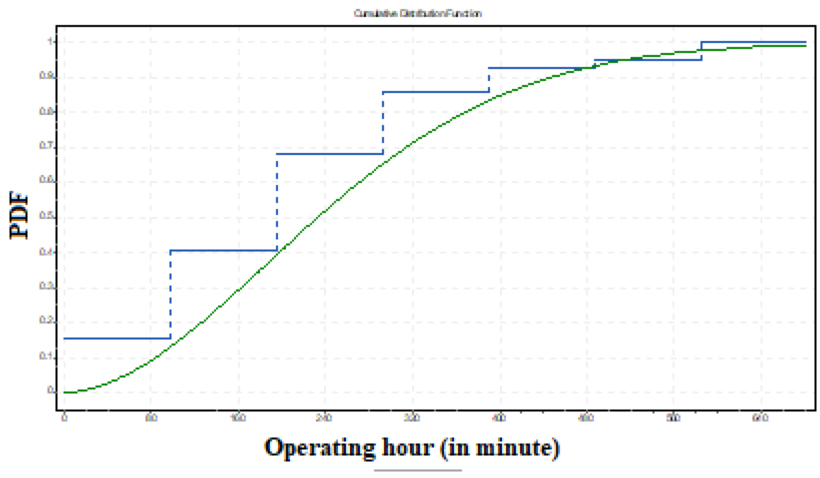


Figure 5.13: CDF distribution for C1 (obtained from Easyfit)

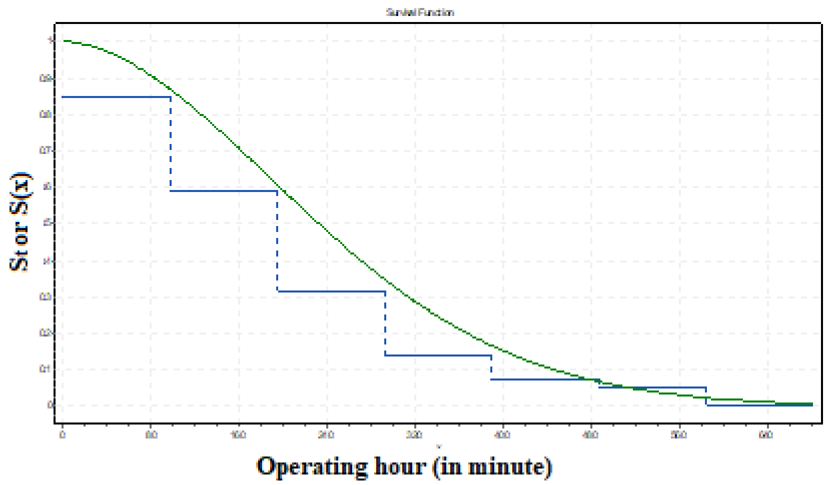


Figure 5.14: Survival function plotting for C1 (obtained from Easyfit)

5.4.2 Weibull plot of component 2

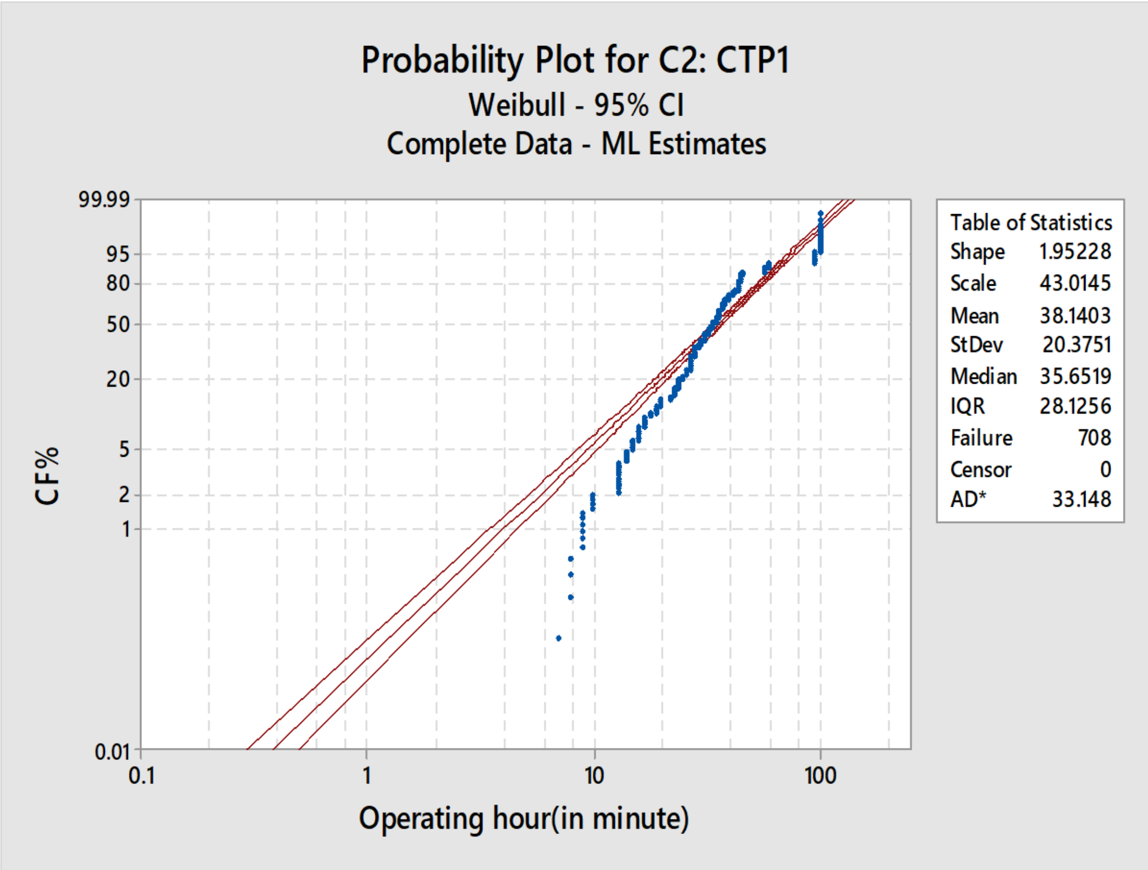
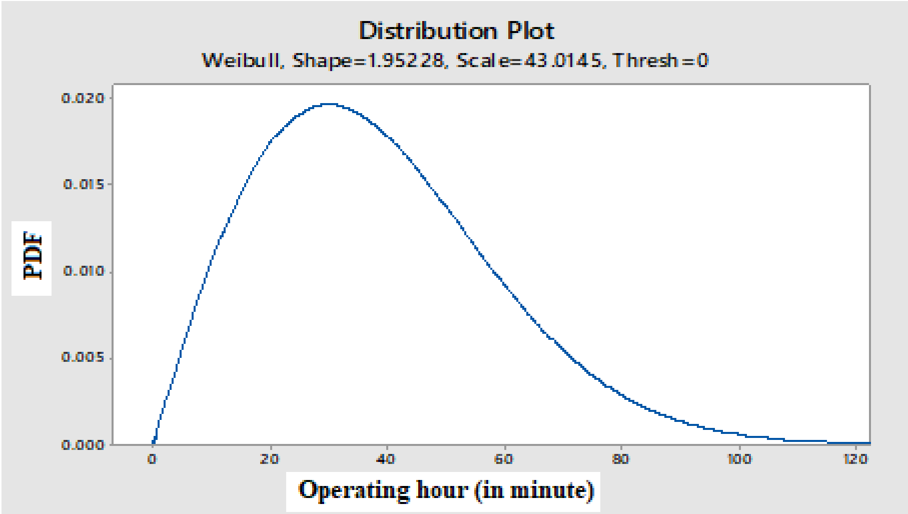
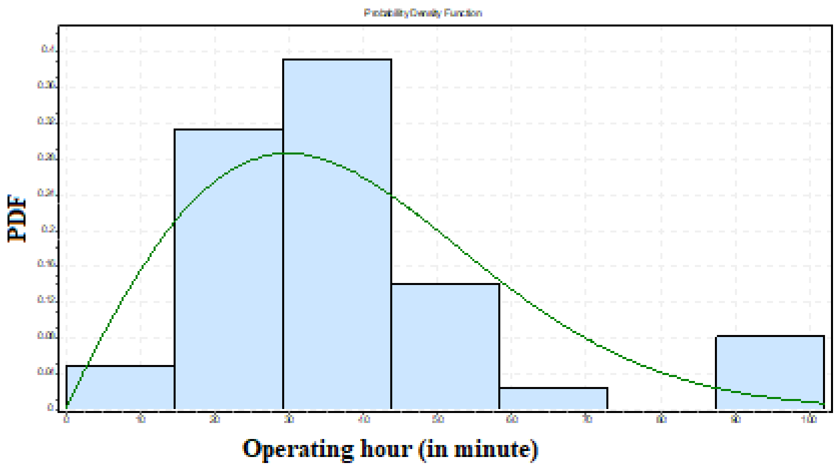


Figure 5.15: Weibull plot of component 2 obtained from Minitab17

Figure 5.15 shows Weibull plot for regression analysis of component 2 (C2) i.e. CTP1. It also shows the value of Shape & scale parameter i.e. (β = 1.95228 & Ƞ = 43.0145) which is estimated by Minitab17.



(a)



(b)

Figure 5.16: PDF distribution for C2 (a) obtained from Minitab17 & (b) obtained from Easyfit

Figure 5.16 (a) & (b) show the distribution of probability density function that describes the failure characteristics of the component 2 whereas Figure 5.17 shows the cumulative distribution function (CDF) of failure rate i.e. reliability and Figure 5.18 shows the survival function plotting for survival analysis.

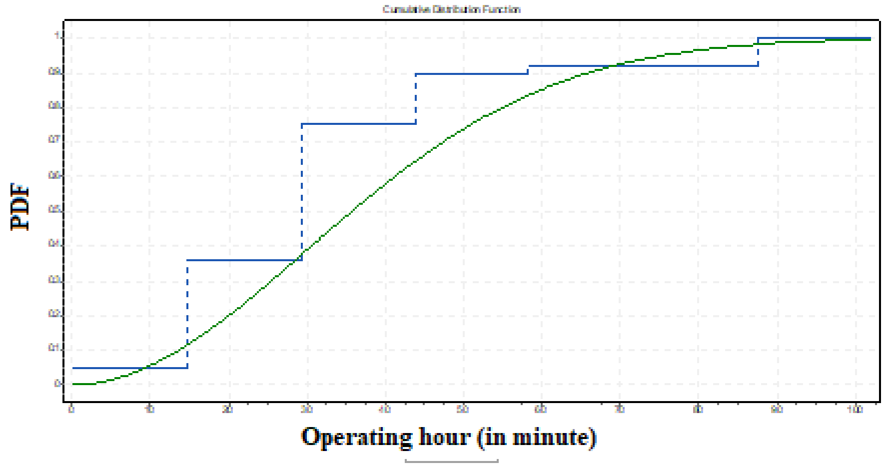


Figure 5.17: Distribution of CDF for C2 obtained from Easyfit

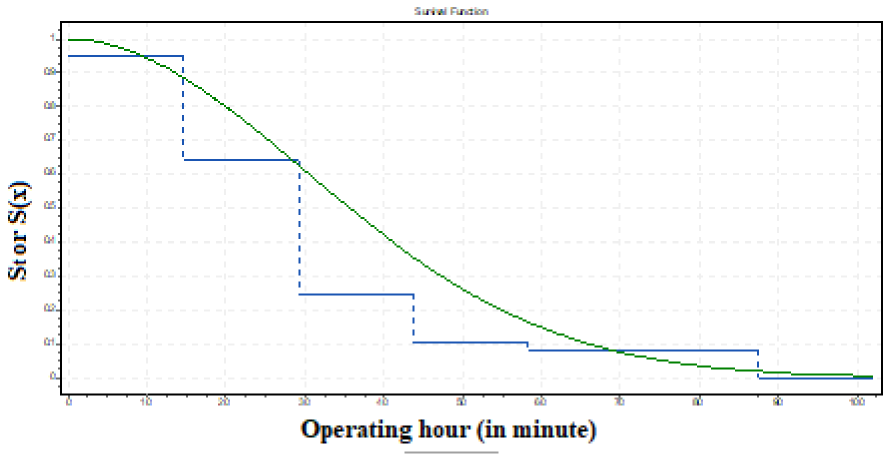


Figure 5.18: Plotting of Survival function for C2 obtained from Easyfit

5.4.3 Weibull plot of component 3

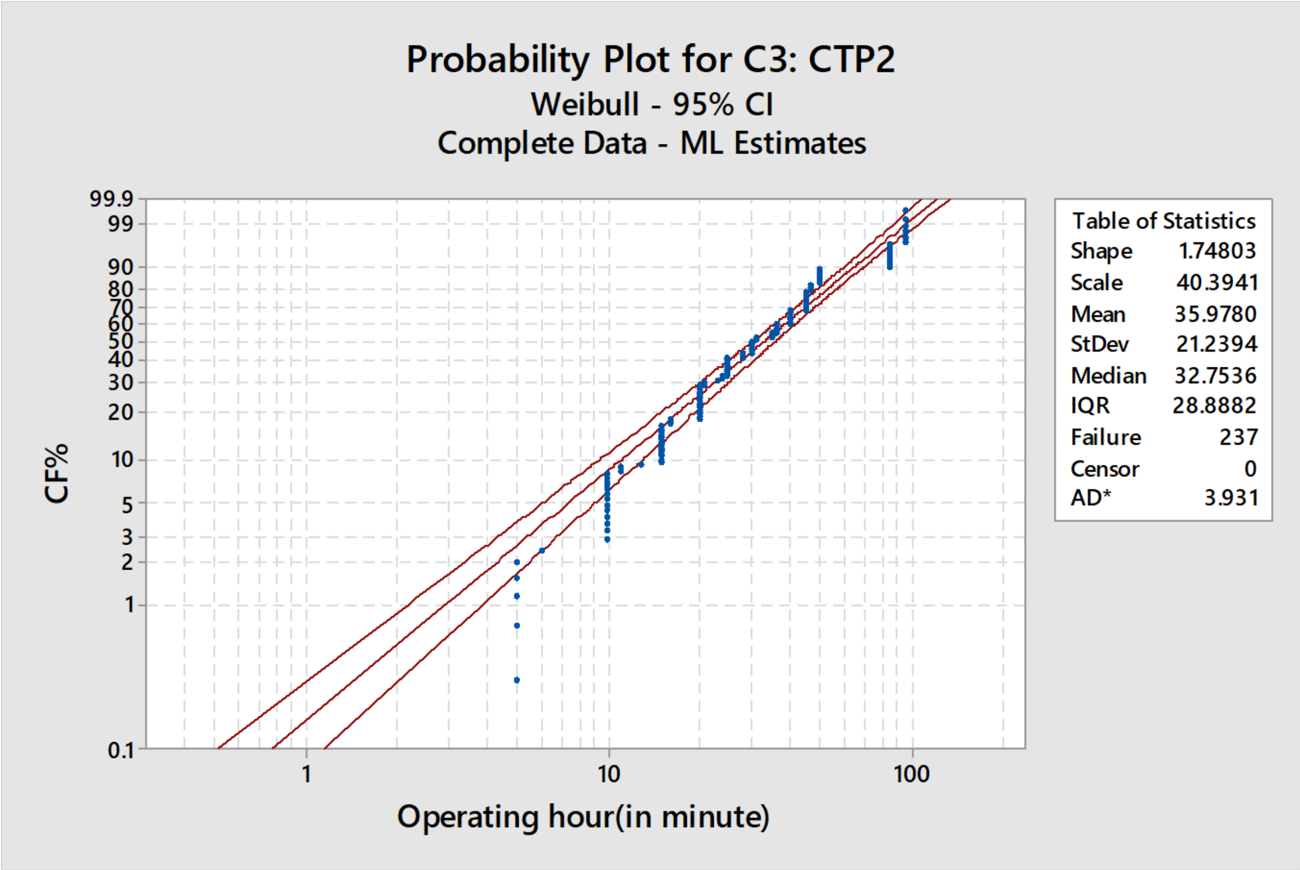
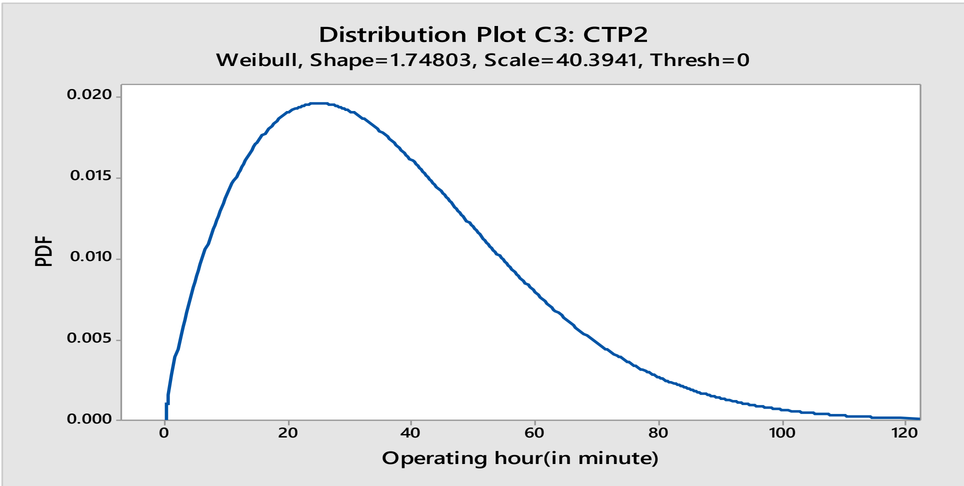
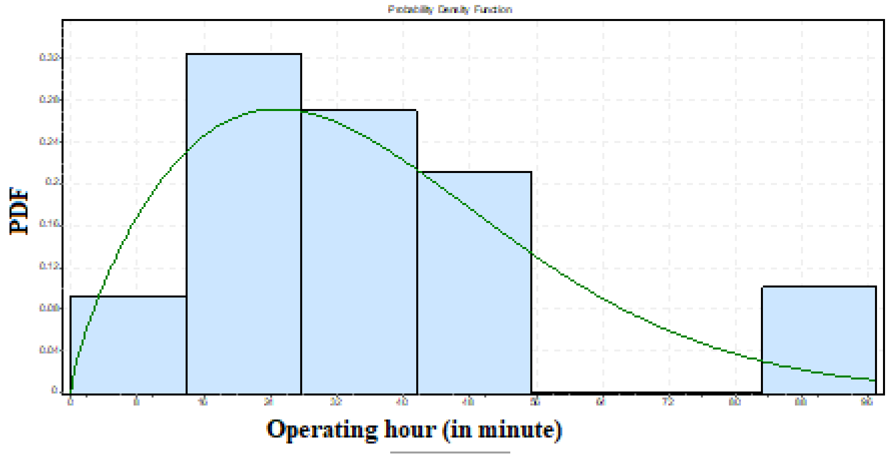


Figure 5.19: Weibull plot of component 3 obtained from Minitab17

Figure 5.19 shows Weibull plot for regression analysis of component 3 (C3) i.e. CTP2. It also shows the value of Shape & scale parameter i.e. (β = 1.74803 & ƞ = 40.3941) which is estimated by Minitab17.



(a)



(b)

Figure 5.20: PDF distribution plotting of C3 (a) obtained from Minitab17 & (b) obtained from Easyfit

Figures 5.20 (a) & (b) show the PDF distribution plotting that describes the failure characteristics of the component 3 whereas Figure 5.21 shows the cumulative distribution function (CDF) of failure rate i.e. reliability and Figure 5.22 shows the survival function for survival analysis.

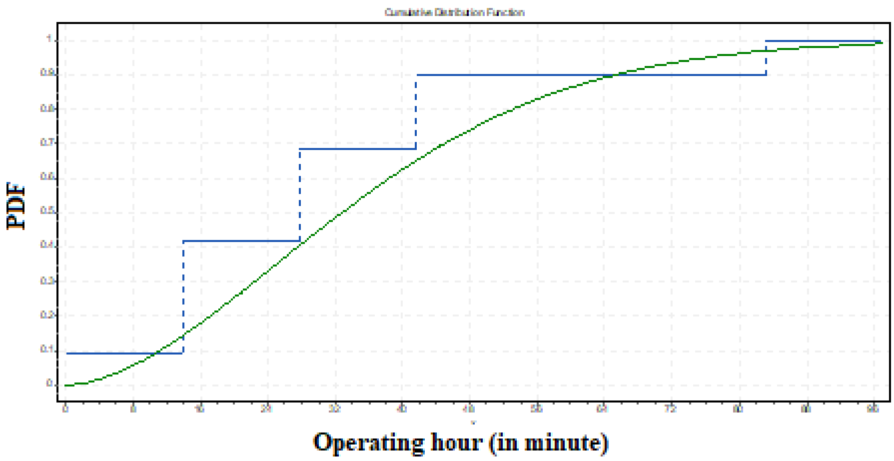


Figure 5.21: Distribution of CDF for C3 obtained from Easyfit

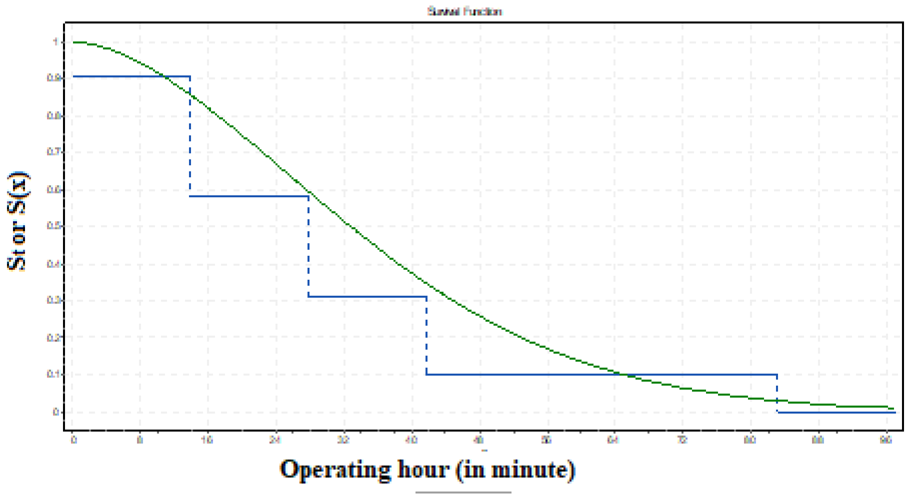


Figure 5.22: Survival function plotting for C3 obtained from Easyfit

5.4.4 Weibull plot of sub-component 1

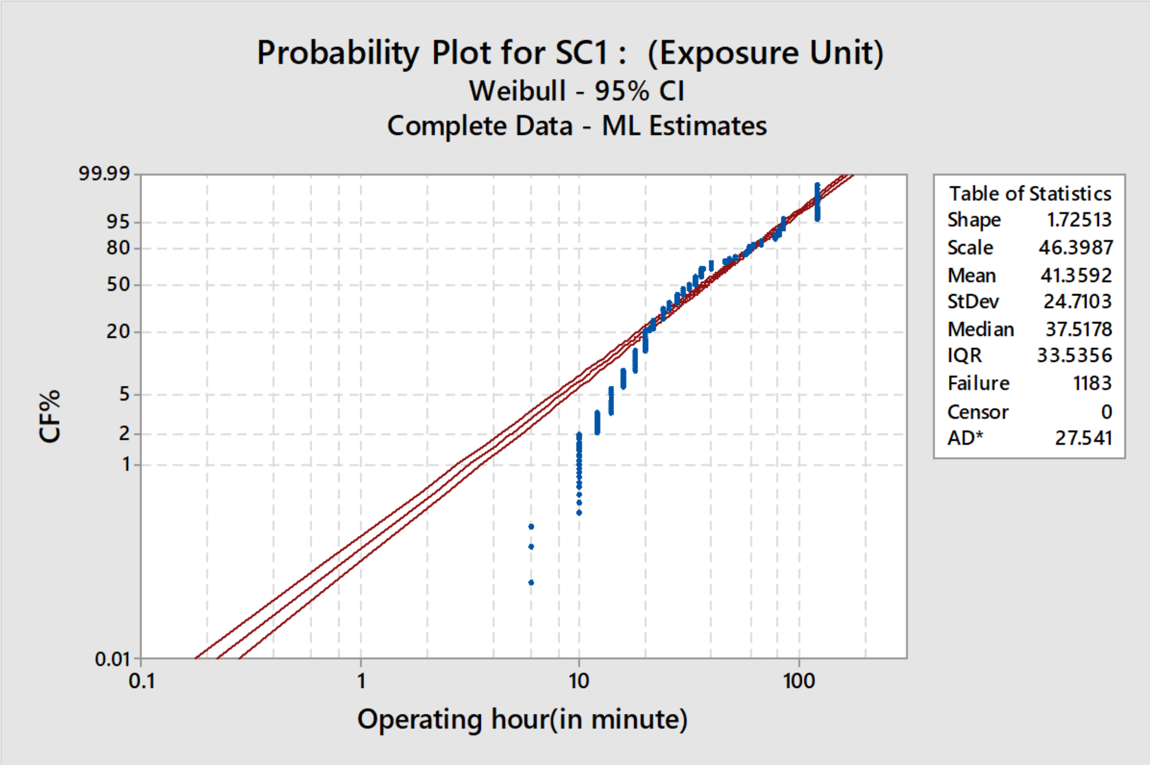
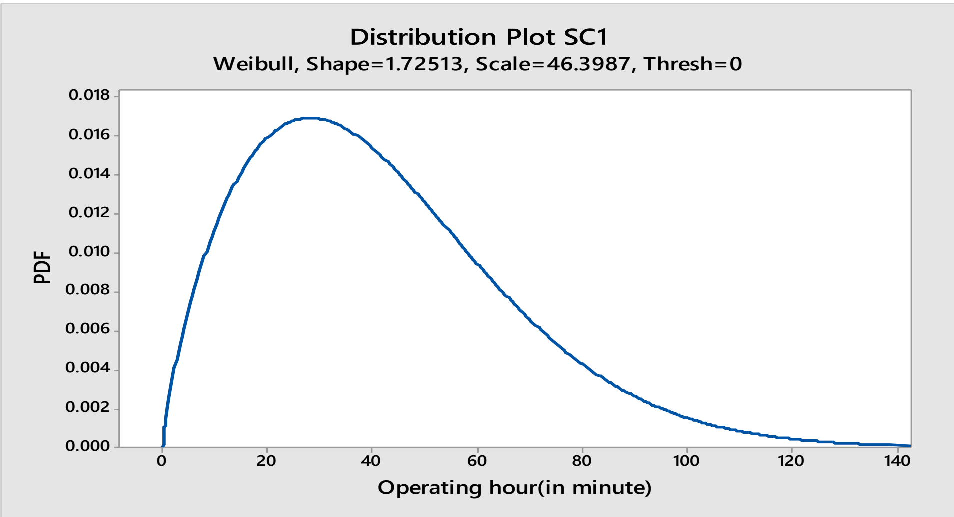
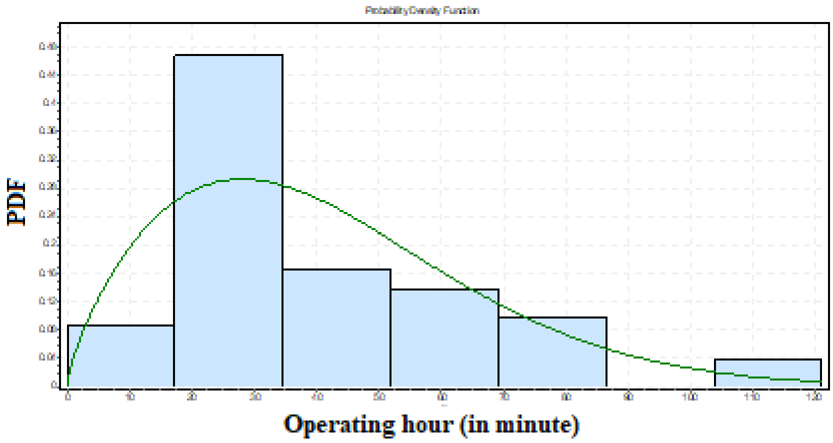


Figure 5.23: Weibull plot of sub-component 1 (SC1) obtained from Minitab17

Figure 5.23 shows Weibull plot for regression analysis of sub-component 1 (SC1) i.e. exposure unit. It also shows the value of Shape & scale parameter i.e. (β = 1.72513 & Ŋ = 46.3987) which is estimated by Minitab17.



(a)



(b)

Figure 5.24: PDF distribution plotting of SC1 (a) obtained from Minitab17 & (b) obtained from Easyfit

Figures 5.24 (a) & (b) show the PDF distribution plotting that describes the failure characteristics of the sub-component 1 whereas Figure 5.25 shows the cumulative distribution function (CDF) of failure rate i.e. reliability and Figure 5.26 shows the survival function for survival analysis.

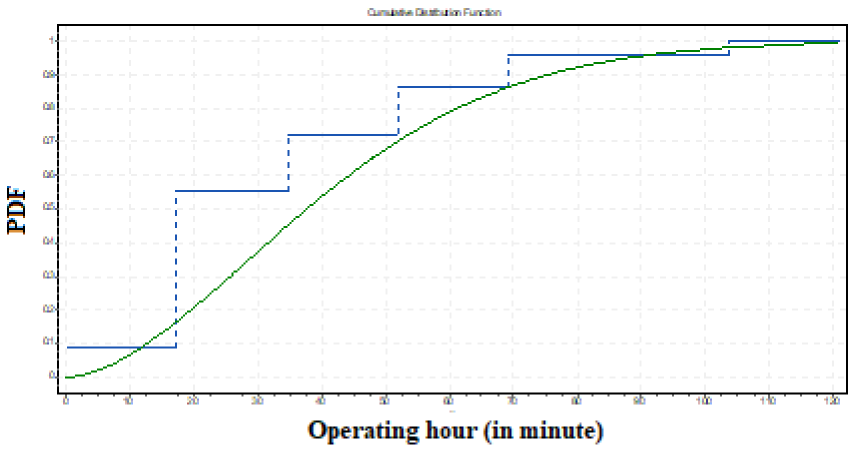


Figure 5.25: Distribution of CDF for SC1 obtained from Easyfit

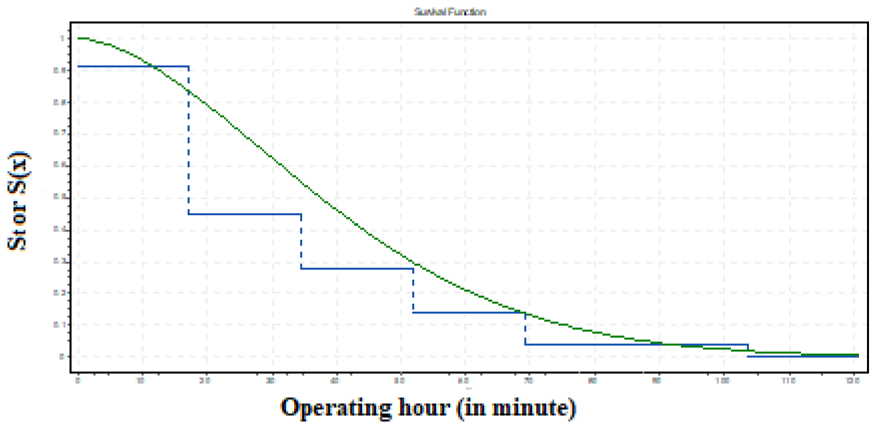


Figure 5.26: Survival function plotting for SC1 obtained from Easyfit

5.4.5 Weibull plot of sub-component 2

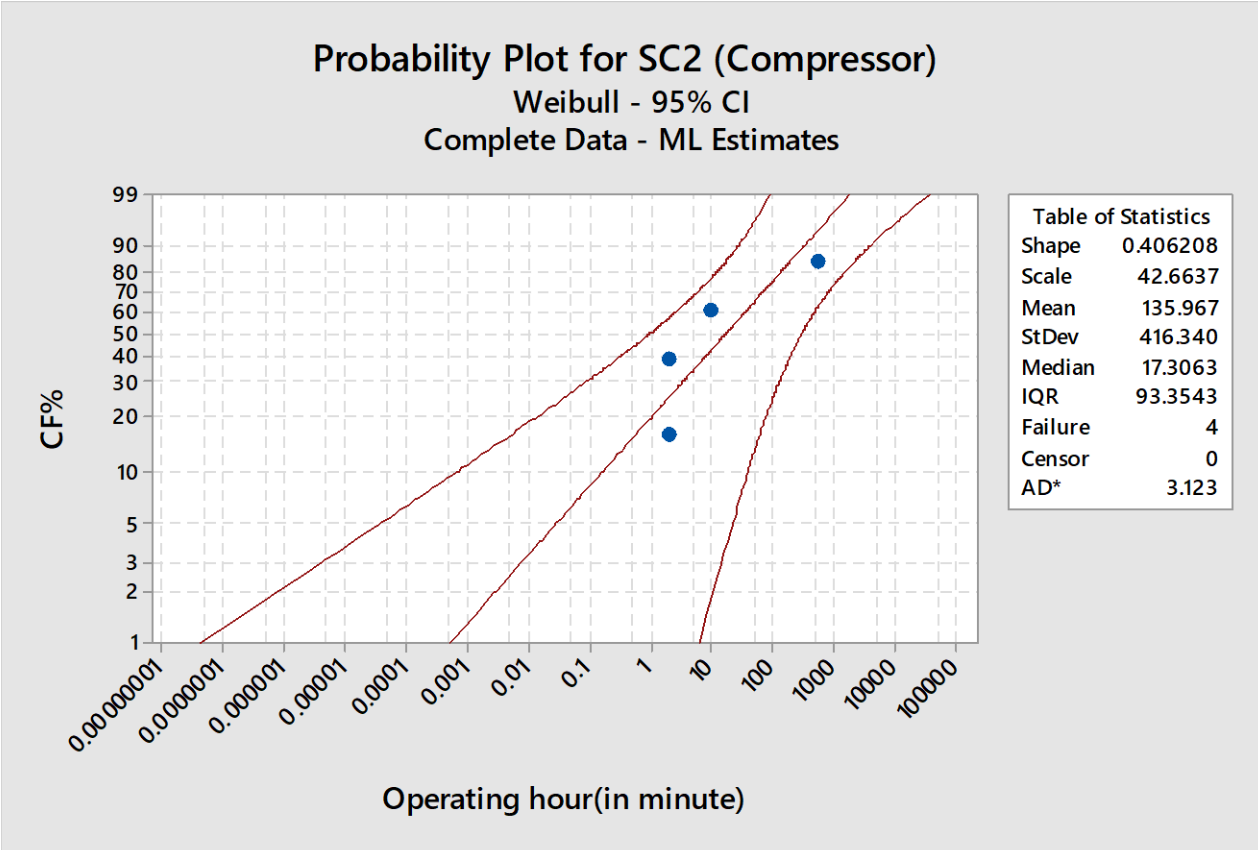
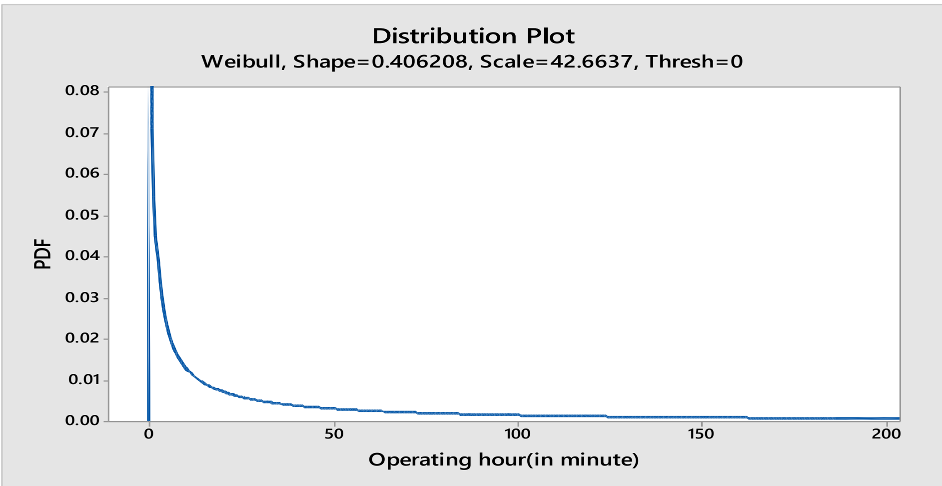
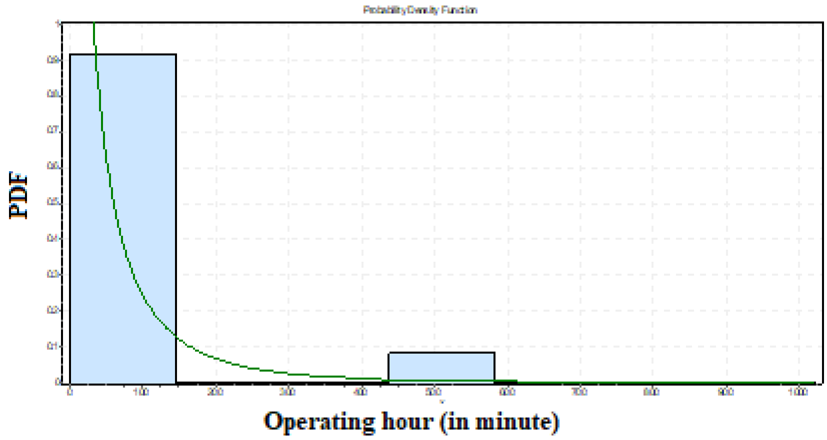


Figure 5.27: Weibull plot of sub-component 2 (SC2)

Figure 5.27 shows Weibull plot for regression analysis of sub-component 2 (SC2) i.e. Compressor 1. It also shows the value of Shape & scale parameter i.e. (β = 0.406208 & Ƞ = 42.6637) which is estimated by Minitab17.



(a)



(b)

Figure 5.28: PDF distribution plotting of SC2 (a) obtained from Minitab17 & (b) obtained from Easyfit

Figures 5.28 (a) & (b) show the PDF distribution plotting that describes the failure characteristics of the sub-component 1 whereas Figure 5.29 shows the cumulative distribution function (CDF) of failure rate i.e. reliability and Figure 5.30 shows the survival function for survival analysis.

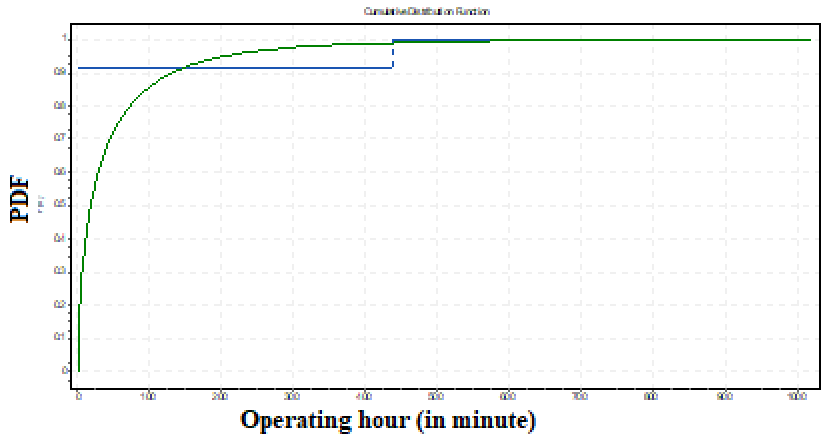


Figure 5.29: Distribution of CDF for SC2 obtained from Easyfit

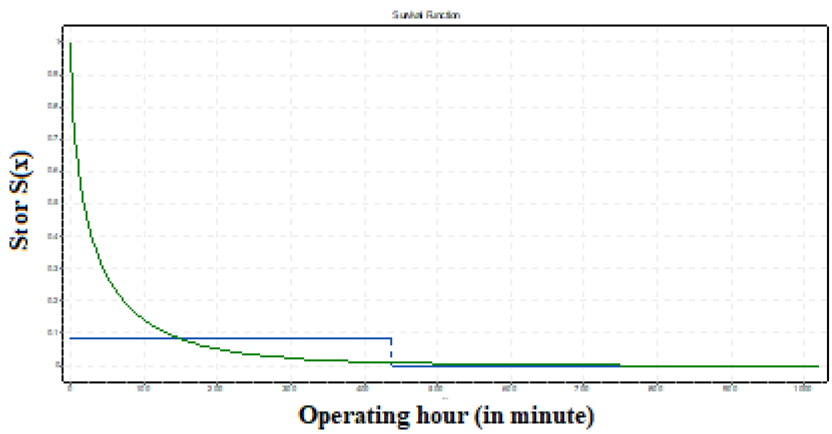


Figure 5.30: Survival function plotting for SC2 obtained from Easyfit

5.5 Survival Analysis or Kaplan-Meier Estimation

Kaplan-Meier estimation [91] is very much important for survival analysis of reliability. Survival rates for all the components and subcomponents are determined by using equation 3.15 and for the purpose of estimation of survival probability "MINITAB17" is used. Table 5.6 to Table 5.10 show the above estimation for different components and subcomponents used in the study. It is important to note that total number of failures of component 1 (C1), component 2 (C2), component 3 (C3), sub-component 1 (SC1) & subcomponent 2 (SC2) are respectively 507, 708, 237, 1183 & 4 (as shown in Table 4.1 – 4.5). Figure 5.31 to Figure 5.35 show the graphical representation or pictorial view of survival analysis of different components and sub-components that are also obtained from Minitab17.

Table 5.6: Kaplan-Meier Estimation for component 1

Operating hour (in minute)	Number at Risk	Number Failed	Survival Probability	Standard Error
18	507	1	0.998028	0.0019704
71	506	3	0.992110	0.0039292
73	503	1	0.990138	0.0043886

74	502	2	0.986193	0.0051823
75	500	14	0.958580	0.0088494
76	486	2	0.954635	0.0092422
77	484	8	0.938856	0.0106408
78	476	6	0.927022	0.0115515
79	470	4	0.919132	0.0121080
80	466	3	0.913215	0.0125027
81	463	1	0.911243	0.0126303
82	462	3	0.905325	0.0130021
83	459	12	0.881657	0.0143456
85	447	6	0.869822	0.0149444
86	441	5	0.859961	0.0154121
88	436	5	0.850099	0.0158538
89	431	1	0.848126	0.0159392
95	430	1	0.846154	0.0160237
102	429	4	0.838264	0.0163527
108	425	4	0.830375	0.0166678
115	421	2	0.826430	0.0168204
122	419	4	0.818540	0.0171161
124	415	3	0.812623	0.017330
127	412	2	0.808679	0.0174689
131	410	2	0.804734	0.0176050
134	408	13	0.779093	0.0184245
144	395	3	0.773176	0.0185986
147	392	9	0.755424	0.0190897
150	383	4	0.747535	0.0192936

157	379	5	0.737673	0.0195366
161	374	5	0.727811	0.0197670
164	369	3	0.721893	0.0198993
168	366	5	0.712032	0.0201103
171	361	6	0.700197	0.0203481
175	355	7	0.686391	0.0206052
183	348	6	0.674556	0.0208086
186	342	30	0.615385	0.0216064
194	312	12	0.591716	0.0218290
203	300	3	0.585799	0.0218764
204	297	11	0.564103	0.0220225
209	286	9	0.546351	0.0221102
219	277	24	0.499014	0.0222057
223	253	9	0.481262	0.0221902
239	244	9	0.463511	0.0221466
240	235	6	0.45167	0.0221018
246	229	10	0.431953	0.0219992
248	219	7	0.418146	0.0219062
253	212	6	0.406312	0.0218125
255	206	9	0.388560	0.0216472
257	197	14	0.360947	0.0213298
258	183	11	0.339250	0.0210269
262	172	5	0.329389	0.0208730
286	167	6	0.317554	0.0206747
300	161	9	0.299803	0.0203481
302	152	11	0.278107	0.0198993

310	141	25	0.228797	0.0186554
331	116	19	0.191321	0.0174689
340	97	17	0.157791	0.0161900
356	80	8	0.142012	0.0155024
408	72	9	0.124260	0.0146504
411	63	14	0.096647	0.0131226
474	49	12	0.072978	0.0115515
528	37	12	0.049310	0.0096157
682	25	25	0.000000	0.0000000

Table 5.7: Kaplan-Meier Estimation for component 2

Operating hour (in minute)	Number at Risk	Number Failed	Survival Probability	Standard Error
7	708	1	0.998588	0.0014114
8	707	3	0.994350	0.0028169
9	704	6	0.985876	0.0044348
10	698	4	0.980226	0.0052323
13	694	13	0.961864	0.0071979
14	681	7	0.951977	0.0080356
15	674	8	0.940678	0.0088779
16	666	14	0.920904	0.0101430
17	652	12	0.903955	0.0110737
18	640	4	0.898305	0.0113591
19	636	10	0.884181	0.0120266

20	626	12	0.867232	0.0127526
22	614	7	0.857345	0.0131433
23	607	18	0.831921	0.0140534
24	589	20	0.803672	0.0149284
25	569	10	0.789548	0.0153197
26	559	14	0.769774	0.0158213
27	545	50	0.699153	0.0172362
28	495	36	0.648305	0.0179455
29	459	7	0.638418	0.0180567
30	452	16	0.615819	0.0182801
31	436	33	0.569209	0.0186103
32	403	27	0.531073	0.0187548
33	376	9	0.518362	0.0187785
34	367	19	0.491525	0.0187885
35	348	28	0.451977	0.0187043
36	320	41	0.394068	0.0183646
37	279	30	0.351695	0.0179455
38	249	20	0.323446	0.0175807
39	229	10	0.309322	0.0173711
40	219	21	0.279661	0.0168682
41	198	12	0.262712	0.0165402
42	186	11	0.247175	0.0162119
44	175	47	0.180791	0.0144634
45	128	26	0.144068	0.0131973
46	102	12	0.127119	0.0125189
57	90	15	0.105932	0.0115660

59	75	17	0.081921	0.0103067
95	58	28	0.042373	0.0075705
102	30	30	0.000000	0.0000000

Table 5.8: Kaplan-Meier Estimation for component 3

Operating hour (in minute)	Number at Risk	Number Failed	Survival Probability	Standard Error
5	237	5	0.978903	0.0093348
6	232	1	0.974684	0.0102037
10	231	13	0.919831	0.0176393
11	218	2	0.911392	0.0184592
13	216	1	0.907173	0.0188499
15	215	17	0.835443	0.0240848
16	198	4	0.818565	0.0250330
20	194	26	0.708861	0.0295091
21	168	3	0.696203	0.0298735
23	165	3	0.683544	0.0302110
24	162	3	0.670886	0.0305227
25	159	21	0.582278	0.0320357
28	138	4	0.565401	0.0321995
30	134	17	0.493671	0.0324759
31	117	5	0.472574	0.0324296
35	112	6	0.447257	0.0322973
36	106	13	0.392405	0.0317176

40	93	19	0.312236	0.0301014
45	74	25	0.206751	0.0263060
47	49	8	0.172996	0.0245696
50	41	17	0.101266	0.0195962
86	24	16	0.033755	0.0117311
97	8	8	0.000000	0.0000000

Table 5.9: Kaplan-Meier Estimation sub-component 1

Operating hour (in minute)	Number at Risk	Number Failed	Survival Probability	Standard Error
6	1183	3	0.997464	0.0014623
10	1180	21	0.979713	0.0040989
12	1159	15	0.967033	0.0051912
14	1144	30	0.941674	0.0068138
16	1114	34	0.912933	0.0081970
18	1080	56	0.865596	0.0099168
20	1024	89	0.790363	0.0118346
21	935	9	0.782756	0.0119893
22	926	49	0.741336	0.0127316
24	877	78	0.675402	0.0136133
26	799	36	0.644970	0.0139126
28	763	76	0.580727	0.0143464
30	687	54	0.535080	0.0145013
32	633	29	0.510566	0.0145338
34	604	78	0.444632	0.0144477

36	526	83	0.374472	0.0140715
37	443	16	0.360947	0.0139636
40	427	56	0.313609	0.0134893
46	371	21	0.295858	0.0132703
48	350	22	0.277261	0.0130150
52	328	24	0.256974	0.0127044
57	304	27	0.234150	0.0123120
58	277	27	0.211327	0.0118695
60	250	24	0.191040	0.0114297
62	226	29	0.166526	0.0108316
68	197	34	0.137785	0.0100211
78	163	37	0.106509	0.0089690
82	126	38	0.074387	0.0076291
86	88	41	0.039730	0.0056789
121	47	47	0.000000	0.0000000

Table 5.10: Kaplan-Meier Estimation for sub-component 2

Operating hour (in minute)	Number at Risk	Number Failed	Survival Probability	Standard Error
2	4	2	0.50	0.250000
10	2	1	0.25	0.216506
571	1	1	0.00	0.000000

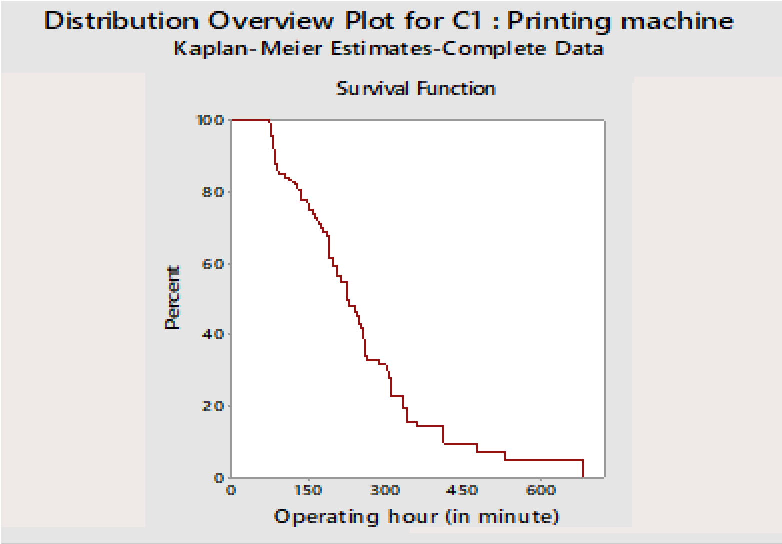


Figure 5.31: Kaplan-Meier survival distribution for C1

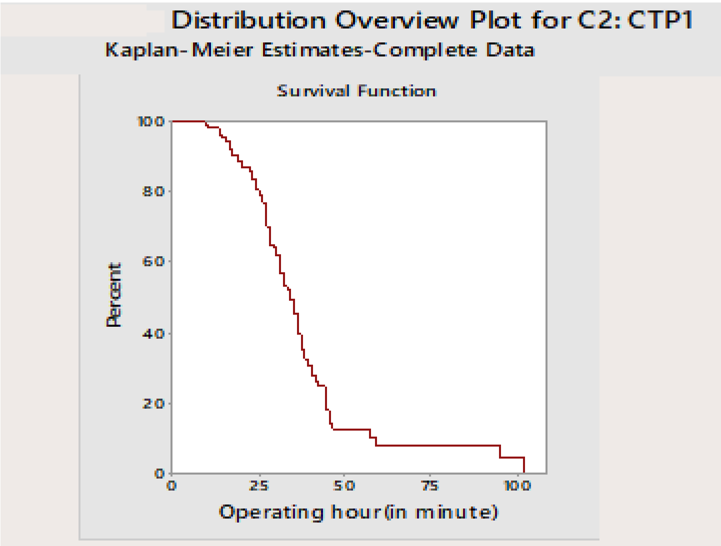


Figure 5.32: Kaplan-Meier survival distribution for C2

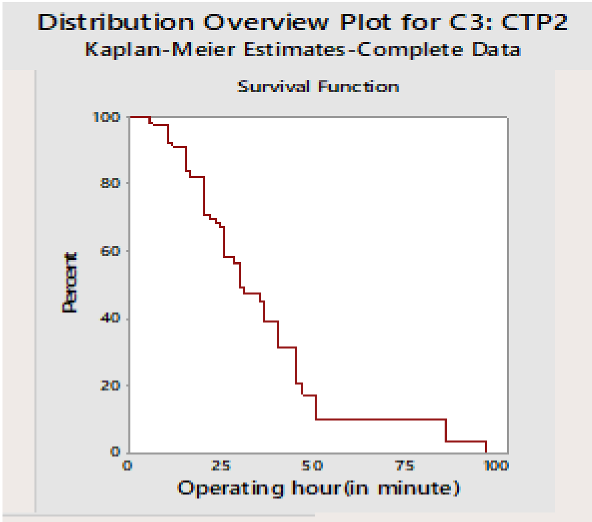


Figure 5.33: Kaplan-Meier survival distribution for C3

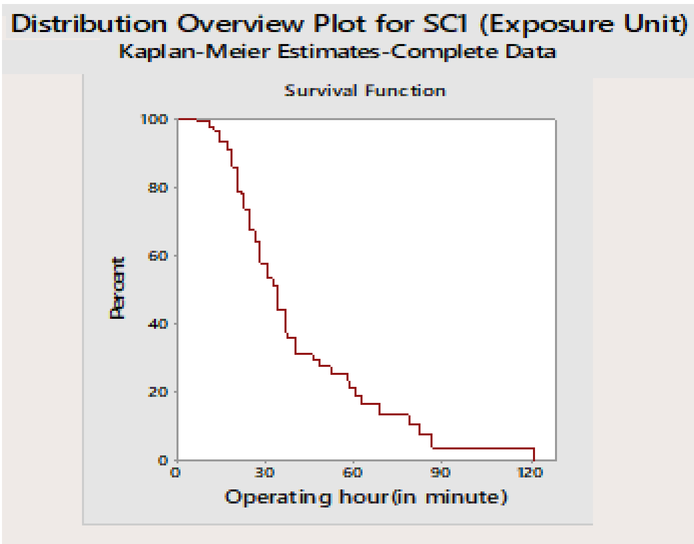


Figure 5.34: Kaplan-Meier survival distribution for SC1

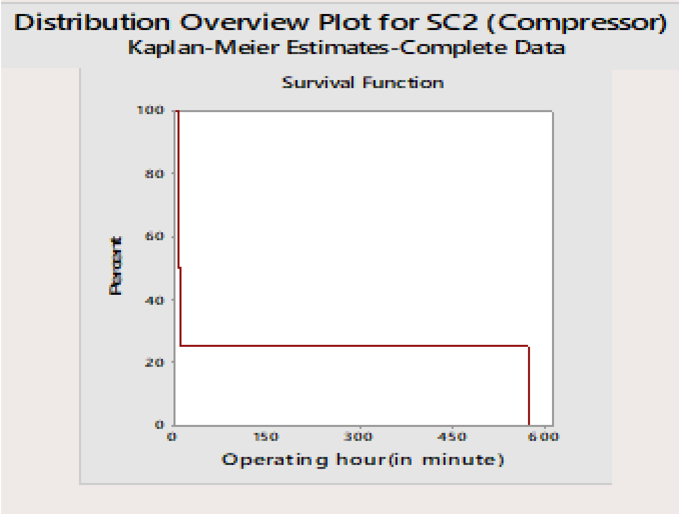


Figure 5.35: Kaplan-Meier survival distribution for SC2

5.6 Analysis of Reliability and Failure Probability

Reliability analysis of the selected components of the press has been carried out with due consideration of failure. Failure probability for the selected components has been estimated by equation 3.18 and the reliability function for the components has been calculated by using equation 3.11. Table 5.11 shows the corresponding results of the above and Figure 5.36 & Figure 5.37 shows the graphical representations of failure and reliability analysis respectively.

Table 5.11: Reliability and Failure Probability of various components & subcomponents

Sl. No.	**Name of component**	**Failure Probability**	**Reliability (in %)**
1	Printing Machine [C1]	0.553133696	44.68663041
2	CTP 1 [C2]	0.735441421	26.45585792
3	CTP 2 [C3]	0.538981219	46.10187813
4	Exposure Unit [SC1]	0.776748064	22.32519361
5	Compressor 1 (Big) [SC2]	0.177805814	82.2194186

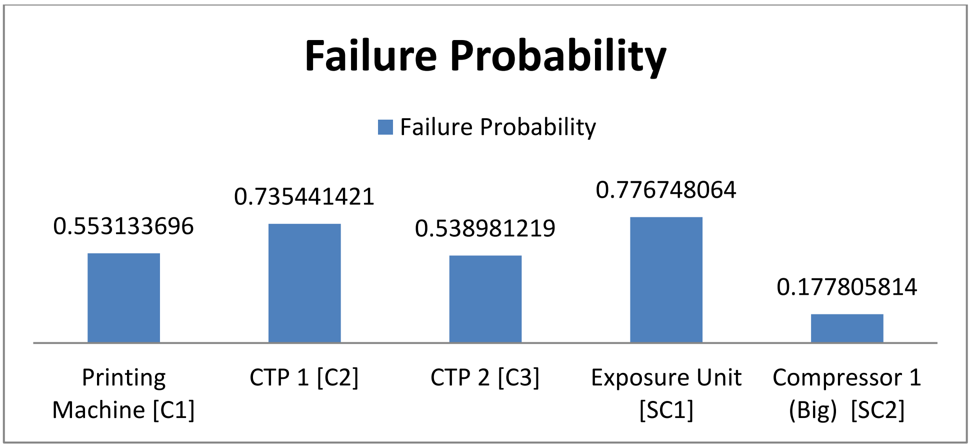


Figure 5.36: Failure probability of various components & subcomponents

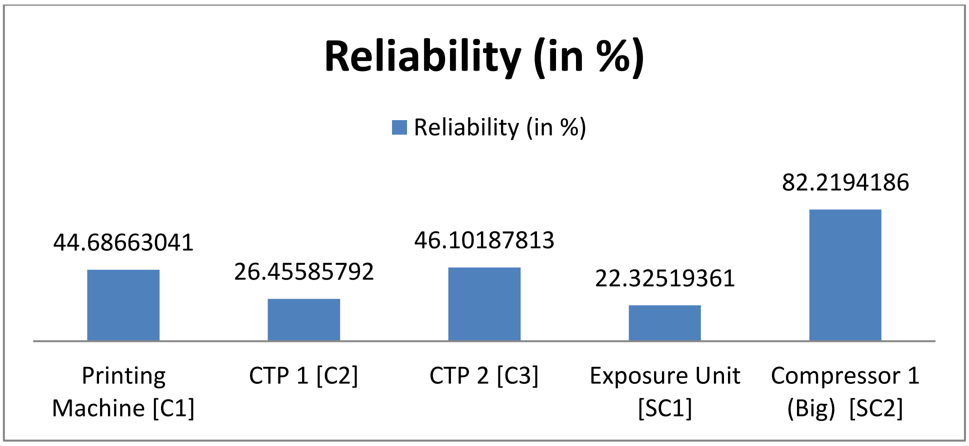


Figure 5.37: Reliability of various components & subcomponents

5.7 Availability Analysis of various components & subcomponents

By the formula used in equation 3.6 & equation 3.8 availability analysis is done. The estimation of availability for all the components and sub-components are described from Table 5.12 to Table 5.16. Figure 5.38 to Figure 5.42 show the corresponding availability plots where MTBF, MTTR & MDT are expressed as equation 5.1, 5.2 & 5.3 respectively

MTBF = (Operational time / failure no) ....(5.1)

MTTR = (Repair time / no of repair) ....(5.2)

MDT = (Downtime / failure no) ....(5.3)

Table 5.12: Estimation of availability of component 1

No. of Days	Operational time (in minute)	Failure no	MTBF	Down time (in minute)	Repair time (in minute)	MTTR	Ain	MDT	Aop
1	75	2	37.5	10	10	5	0.88235	5	0.88235
2	220	9	24.44444	81	81	9	0.7309	9	0.7309
3	356	8	44.5	111	111	13.875	0.76231	13.875	0.76231
4	131	2	65.5	9	9	4.5	0.93571	4.5	0.93571
5	71	3	23.66667	8	8	2.66667	0.89873	2.66667	0.89873
6	77	3	25.66667	22	22	7.33333	0.77778	7.33333	0.77778
7	77	2	38.5	10	10	5	0.88506	5	0.88506
8	76	2	38	29	29	14.5	0.72381	14.5	0.72381
9	331	11	30.09091	131	124	11.2727	0.72747	11.9091	0.71645
10	302	11	27.45455	200	195	17.7273	0.60765	18.1818	0.60159
11	157	5	31.4	60	57	11.4	0.73364	12	0.7235
12	83	2	41.5	24	24	12	0.7757	12	0.7757
13	115	2	57.5	10	10	5	0.92	5	0.92
14	75	5	15	39	39	7.8	0.65789	7.8	0.65789
15	0	0	0	0	0	0	0	0	0
16	186	16	11.625	108	101	6.3125	0.64808	6.75	0.63265
17	300	9	33.33333	100	95	10.5556	0.75949	11.1111	0.75
18	147	4	36.75	49	49	12.25	0.75	12.25	0.75
19	88	5	17.6	53	50	10	0.63768	10.6	0.62411
20	85	4	21.25	49	49	12.25	0.63433	12.25	0.63433
21	102	4	25.5	22	22	5.5	0.82258	5.5	0.82258
22	78	3	26	47	47	15.6667	0.624	15.6667	0.624
23	194	12	16.16667	216	216	18	0.47317	18	0.47317
24	204	6	34	67	60	10	0.77273	11.1667	0.75277
25	124	3	41.33333	18	18	6	0.87324	6	0.87324
26	86	2	43	22	22	11	0.7963	11	0.7963
27	77	2	38.5	13	13	6.5	0.85556	6.5	0.85556
28	83	4	20.75	23	23	5.75	0.78302	5.75	0.78302
29	18	1	18	257	90	90	0.16667	257	0.06545
30	258	11	23.45455	91	88	8	0.74566	8.27273	0.73926
31	246	10	24.6	139	139	13.9	0.63896	13.9	0.63896
32	164	3	54.66667	24	24	8	0.87234	8	0.87234
33	83	2	41.5	12	12	6	0.87368	6	0.87368
34	75	2	37.5	13	13	6.5	0.85227	6.5	0.85227
35	77	1	77	8	8	8	0.90588	8	0.90588
36	80	1	80	5	5	5	0.94118	5	0.94118
37	186	8	23.25	110	105	13.125	0.63918	13.75	0.62838
38	248	7	35.42857	130	130	18.5714	0.65608	18.5714	0.65608
39	150	4	37.5	20	20	5	0.88235	5	0.88235
40	78	1	78	7	7	7	0.91765	7	0.91765

41	108	4	27	22	22	5.5	0.83077	5.5	0.83077
42	75	4	18.75	27	25	6.25	0.75	6.75	0.73529
43	186	6	31	65	63	10.5	0.74699	10.8333	0.74104
44	175	7	25	196	196	28	0.4717	28	0.4717
45	239	9	26.55556	70	70	7.77778	0.77346	7.77778	0.77346
46	161	5	32.2	31	31	6.2	0.83854	6.2	0.83854
47	78	2	39	12	12	6	0.86667	6	0.86667
48	286	6	47.66667	113	53	8.83333	0.84366	18.8333	0.71679
49	223	9	24.77778	139	99	11	0.69255	15.4444	0.61602
50	203	3	67.66667	45	30	10	0.87124	15	0.81855
51	310	25	12.4	293	276	11.04	0.52901	11.72	0.5141
52	411	14	29.35714	124	120	8.57143	0.77401	8.85714	0.76822
53	240	6	40	34	34	5.66667	0.87591	5.66667	0.87591
54	83	2	41.5	10	10	5	0.89247	5	0.89247
55	74	2	37	16	16	8	0.82222	8	0.82222
56	255	9	28.33333	79	76	8.44444	0.77039	8.77778	0.76347
57	81	1	81	7	7	7	0.92045	7	0.92045
58	257	14	18.35714	218	142	10.1429	0.64411	15.5714	0.54105
59	204	5	40.8	59	50	10	0.80315	11.8	0.77567
60	127	2	63.5	33	33	16.5	0.79375	16.5	0.79375
61	147	5	29.4	63	50	10	0.74619	12.6	0.7
62	134	13	10.30769	99	91	7	0.59556	7.61538	0.57511
63	474	12	39.5	78	78	6.5	0.8587	6.5	0.8587
64	682	25	27.28	140	115	4.6	0.85571	5.6	0.82968
65	219	24	9.125	162	126	5.25	0.63478	6.75	0.5748
66	528	12	44	140	128	10.6667	0.80488	11.6667	0.79042
67	75	1	75	5	5	5	0.9375	5	0.9375
68	253	6	42.16667	43	43	7.16667	0.85473	7.16667	0.85473
69	331	8	41.375	54	54	6.75	0.85974	6.75	0.85974
70	340	17	20	194	180	10.5882	0.65385	11.4118	0.6367
71	408	9	45.33333	97	95	10.5556	0.81113	10.7778	0.80792
72	168	5	33.6	79	79	15.8	0.68016	15.8	0.68016
73	262	5	52.4	64	64	12.8	0.80368	12.8	0.80368
74	83	2	41.5	11	11	5.5	0.88298	5.5	0.88298
75	79	2	39.5	12	12	6	0.86813	6	0.86813
76	86	1	86	5	5	5	0.94505	5	0.94505
77	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0
81	144	3	48	29	29	9.66667	0.83237	9.66667	0.83237
82	171	6	28.5	72	72	12	0.7037	12	0.7037
83	82	3	27.33333	65	65	21.6667	0.55782	21.6667	0.55782
84	95	1	95	6	6	6	0.94059	6	0.94059

85	86	2	43	6	6	3	0.93478	3	0.93478
86	183	6	30.5	51	51	8.5	0.78205	8.5	0.78205
87	122	4	30.5	93	88	22	0.58095	23.25	0.56744
88	89	1	89	6	6	6	0.93684	6	0.93684
89	85	2	42.5	13	10	5	0.89474	6.5	0.86735
90	80	2	40	15	15	7.5	0.84211	7.5	0.84211
91	79	2	39.5	22	21	10.5	0.79	11	0.78218
92	73	1	73	11	11	11	0.86905	11	0.86905

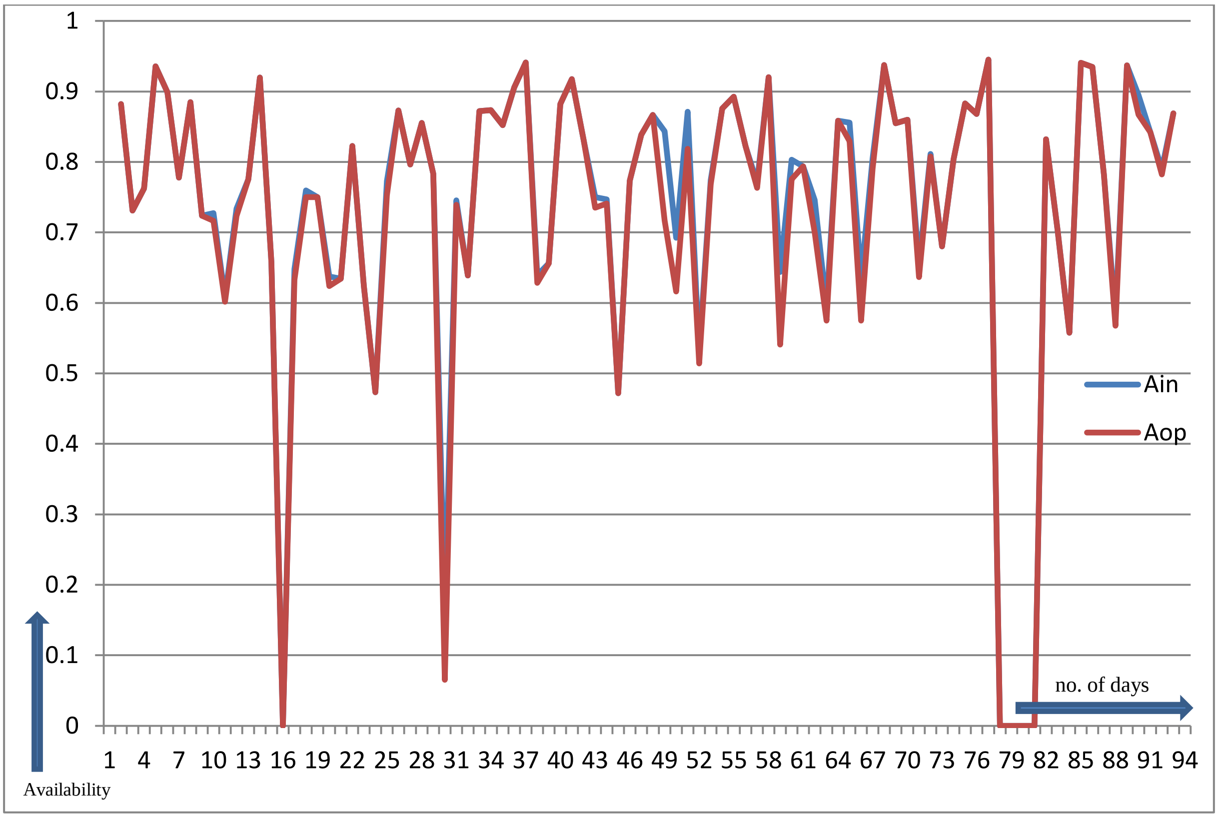


Figure 5.38: Availability of component 1

Table 5.13: Estimation of availability of component 2

No. of Days	Operational time (in minute)	Failure no	MTBF	Down time (in minute)	Repair time (in minute)	MTTR	Ain	MDT	Aop
1	13	3	4.33333	5	5	1.66667	0.72222	1.66667	0.72222
2	16	5	3.2	33	33	6.6	0.32653	6.6	0.32653
3	14	3	4.66667	9	9	3	0.6087	3	0.6087
4	42	11	3.81818	59	59	5.36364	0.41584	5.36364	0.41584
5	9	4	2.25	7	7	1.75	0.5625	1.75	0.5625

6	10	2	5	86	86	43	0.10417	43	0.10417
7	38	9	4.22222	35	35	3.88889	0.52055	3.88889	0.52055
8	37	10	3.7	59	59	5.9	0.38542	5.9	0.38542
9	45	13	3.46154	57	57	4.38462	0.44118	4.38462	0.44118
10	9	2	4.5	36	36	18	0.2	18	0.2
11	46	12	3.83333	43	43	3.58333	0.51685	3.58333	0.51685
12	13	4	3.25	37	37	9.25	0.26	9.25	0.26
13	25	5	5	9	9	1.8	0.73529	1.8	0.73529
14	36	10	3.6	13	13	1.3	0.73469	1.3	0.73469
15	16	4	4	9	9	2.25	0.64	2.25	0.64
16	14	4	3.5	33	33	8.25	0.29787	8.25	0.29787
17	17	4	4.25	56	56	14	0.23288	14	0.23288
18	44	11	4	116	116	10.5455	0.275	10.5455	0.275
19	27	7	3.85714	40	40	5.71429	0.40299	5.71429	0.40299
20	30	8	3.75	98	98	12.25	0.23438	12.25	0.23438
21	35	9	3.88889	56	56	6.22222	0.38462	6.22222	0.38462
22	8	3	2.66667	5	5	1.66667	0.61538	1.66667	0.61538
23	44	12	3.66667	31	31	2.58333	0.58667	2.58333	0.58667
24	0	0	0	0	0	0	0	0	0
25	40	10	4	79	79	7.9	0.33613	7.9	0.33613
26	27	7	3.85714	23	23	3.28571	0.54	3.28571	0.54
27	20	5	4	7	7	1.4	0.74074	1.4	0.74074
28	35	9	3.88889	67	67	7.44444	0.34314	7.44444	0.34314
29	31	8	3.875	47	47	5.875	0.39744	5.875	0.39744
30	17	4	4.25	24	24	6	0.41463	6	0.41463
31	37	10	3.7	51	51	5.1	0.42045	5.1	0.42045
32	31	8	3.875	21	21	2.625	0.59615	2.625	0.59615
33	35	10	3.5	42	42	4.2	0.45455	4.2	0.45455
34	15	4	3.75	20	20	5	0.42857	5	0.42857
35	38	11	3.45455	21	21	1.90909	0.64407	1.90909	0.64407
36	23	6	3.83333	90	90	15	0.20354	15	0.20354
37	33	9	3.66667	58	58	6.44444	0.36264	6.44444	0.36264
38	20	7	2.85714	57	57	8.14286	0.25974	8.14286	0.25974
39	32	9	3.55556	51	51	5.66667	0.38554	5.66667	0.38554
40	24	7	3.42857	33	33	4.71429	0.42105	4.71429	0.42105
41	28	8	3.5	52	52	6.5	0.35	6.5	0.35
42	26	7	3.71429	9	9	1.28571	0.74286	1.28571	0.74286
43	27	7	3.85714	33	33	4.71429	0.45	4.71429	0.45
44	27	7	3.85714	38	38	5.42857	0.41538	5.42857	0.41538
45	28	7	4	44	44	6.28571	0.38889	6.28571	0.38889
46	23	6	3.83333	6	6	1	0.7931	1	0.7931
47	24	7	3.42857	38	38	5.42857	0.3871	5.42857	0.3871
48	27	7	3.85714	34	34	4.85714	0.44262	4.85714	0.44262
49	27	7	3.85714	37	37	5.28571	0.42188	5.28571	0.42188

50	25	5	5	56	56	11.2	0.30864	11.2	0.30864
51	34	10	3.4	66	66	6.6	0.34	6.6	0.34
52	17	4	4.25	50	50	12.5	0.25373	12.5	0.25373
53	31	9	3.44444	45	45	5	0.40789	5	0.40789
54	10	2	5	96	96	48	0.09434	48	0.09434
55	30	8	3.75	50	50	6.25	0.375	6.25	0.375
56	32	9	3.55556	105	105	11.6667	0.23358	11.6667	0.23358
57	28	6	4.66667	94	94	15.6667	0.22951	15.6667	0.22951
58	45	13	3.46154	22	22	1.69231	0.67164	1.69231	0.67164
59	16	5	3.2	112	112	22.4	0.125	22.4	0.125
60	27	8	3.375	41	41	5.125	0.39706	5.125	0.39706
61	59	17	3.47059	82	82	4.82353	0.41844	4.82353	0.41844
62	19	5	3.8	5	5	1	0.79167	1	0.79167
63	44	12	3.66667	77	77	6.41667	0.36364	6.41667	0.36364
64	13	3	4.33333	3	3	1	0.8125	1	0.8125
65	40	11	3.63636	59	59	5.36364	0.40404	5.36364	0.40404
66	7	1	7	1	1	1	0.875	1	0.875
67	34	9	3.77778	86	86	9.55556	0.28333	9.55556	0.28333
68	28	8	3.5	57	57	7.125	0.32941	7.125	0.32941
69	24	6	4	15	15	2.5	0.61538	2.5	0.61538
70	39	10	3.9	63	63	6.3	0.38235	6.3	0.38235
71	95	28	3.39286	209	209	7.46429	0.3125	7.46429	0.3125
72	102	30	3.4	117	117	3.9	0.46575	3.9	0.46575
73	13	3	4.33333	5	5	1.66667	0.72222	1.66667	0.72222
74	31	8	3.875	75	75	9.375	0.29245	9.375	0.29245
75	23	6	3.83333	52	52	8.66667	0.30667	8.66667	0.30667
76	36	11	3.27273	27	27	2.45455	0.57143	2.45455	0.57143
77	15	4	3.75	23	23	5.75	0.39474	5.75	0.39474
78	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0	0
81	29	7	4.14286	85	85	12.1429	0.25439	12.1429	0.25439
82	36	10	3.6	79	79	7.9	0.31304	7.9	0.31304
83	36	10	3.6	118	118	11.8	0.23377	11.8	0.23377
84	37	10	3.7	42	42	4.2	0.46835	4.2	0.46835
85	28	7	4	32	32	4.57143	0.46667	4.57143	0.46667
86	57	15	3.8	87	87	5.8	0.39583	5.8	0.39583
87	22	7	3.14286	27	27	3.85714	0.44898	3.85714	0.44898
88	41	12	3.41667	43	43	3.58333	0.4881	3.58333	0.4881
89	19	5	3.8	49	49	9.8	0.27941	9.8	0.27941
90	44	12	3.66667	112	112	9.33333	0.28205	9.33333	0.28205
91	32	9	3.55556	105	105	11.6667	0.23358	11.6667	0.23358
92	18	4	4.5	30	30	7.5	0.375	7.5	0.375
93	26	7	3.71429	16	16	2.28571	0.61905	2.28571	0.61905

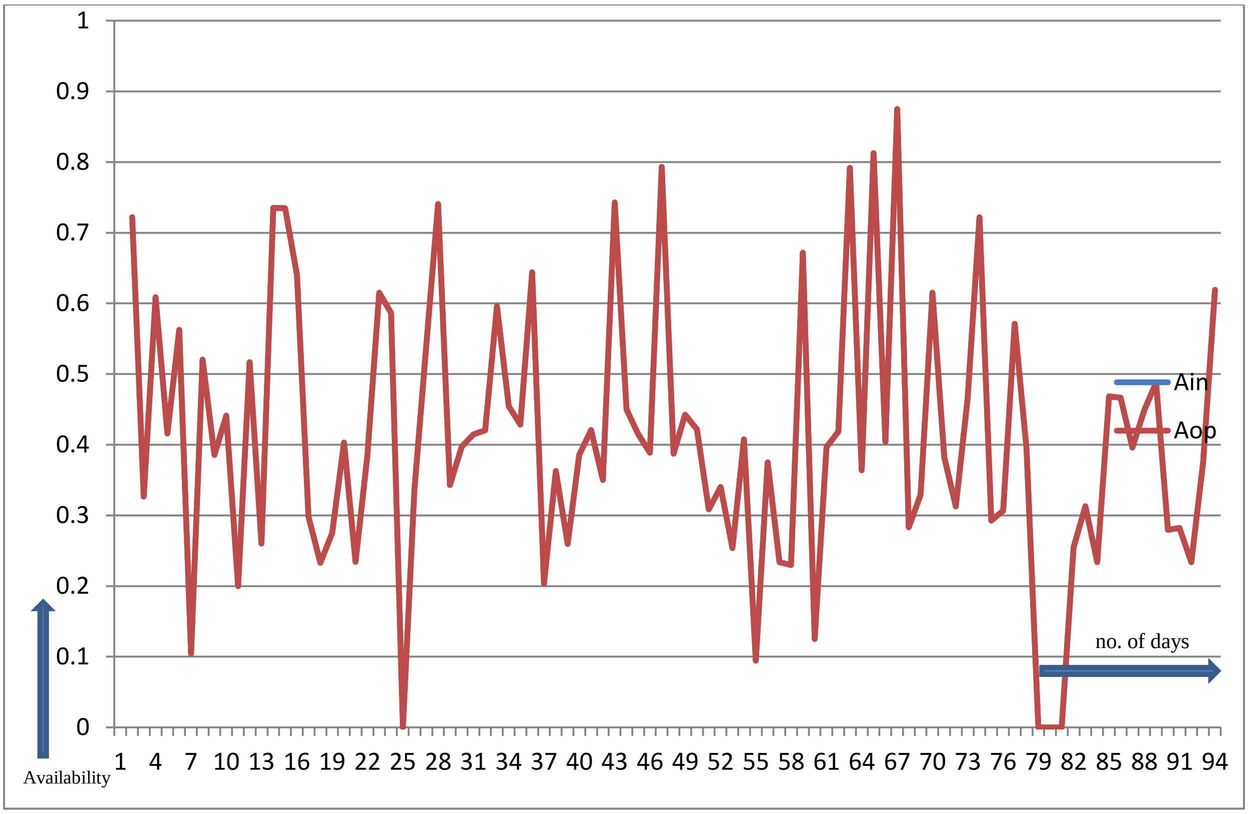


Figure 5.39: Availability of component 2

Table 5.14: Estimation of availability of component 3

No. of Days	Operational time (in minute)	Failure no	MTBF	Down time (in minute)	Repair time (in minute)	MTTR	Ain	MDT	Aop
1	5	0	*	0	0	*	1	*	1
2	0	0	*	0	0	*	0	*	0
3	10	1	10	3	3	3	0.76923	3	0.76923
4	40	5	8	29	29	5.8	0.57971	5.8	0.57971
5	5	1	5	65	65	65	0.07143	65	0.07143
6	25	4	6.25	84	84	21	0.22936	21	0.22936
7	28	4	7	6	6	1.5	0.82353	1.5	0.82353
8	0	0	*	0	0	*	0	*	0
9	10	2	5	60	60	30	0.14286	30	0.14286
10	10	1	10	1	1	1	0.90909	1	0.90909
11	21	2	10.5	135	135	67.5	0.13462	67.5	0.13462
12	10	1	10	25	25	25	0.28571	25	0.28571
13	10	1	10	69	69	69	0.12658	69	0.12658
14	15	1	15	0	0	0	1	0	1
15	16	4	4	9	9	2.25	0.64	2.25	0.64

16	25	4	6.25	25	25	6.25	0.5	6.25	0.5
17	0	0	*	0	0	*	0	*	0
18	15	4	3.75	15	15	3.75	0.5	3.75	0.5
19	15	2	7.5	120	120	60	0.11111	60	0.11111
20	11	0	*	0	0	*	1	*	1
21	97	8	12.125	59	59	7.375	0.62179	7.375	0.62179
22	20	2	10	1	1	0.5	0.95238	0.5	0.95238
23	50	12	4.16667	51	51	4.25	0.49505	4.25	0.49505
24	35	6	5.83333	125	125	20.8333	0.21875	20.8333	0.21875
25	23	3	7.66667	2	2	0.66667	0.92	0.66667	0.92
26	5	1	5	60	60	60	0.07692	60	0.07692
27	10	1	10	41	41	41	0.19608	41	0.19608
28	11	0	*	0	0	*	1	*	1
29	5	1	5	70	70	70	0.06667	70	0.06667
30	31	5	6.2	60	60	12	0.34066	12	0.34066
31	6	0	*	0	0	*	1	*	1
32	36	7	5.14286	36	36	5.14286	0.5	5.14286	0.5
33	0	0	*	0	0	*	0	*	0
34	20	5	4	89	89	17.8	0.18349	17.8	0.18349
35	5	0	*	0	0	*	1	*	1
36	30	7	4.28571	35	35	5	0.46154	5	0.46154
37	86	16	5.375	86	86	5.375	0.5	5.375	0.5
38	20	3	6.66667	6	6	2	0.76923	2	0.76923
39	36	6	6	65	65	10.8333	0.35644	10.8333	0.35644
40	10	0	*	0	0	*	1	*	1
41	5	1	5	65	65	65	0.07143	65	0.07143
42	13	1	13	48	48	48	0.21311	48	0.21311
43	11	1	11	27	27	27	0.28947	27	0.28947
44	15	2	7.5	8	8	4	0.65217	4	0.65217
45	45	8	5.625	90	90	11.25	0.33333	11.25	0.33333
46	21	1	21	57	57	57	0.26923	57	0.26923
47	6	1	6	39	39	39	0.13333	39	0.13333
48	10	1	10	30	30	30	0.25	30	0.25
49	20	3	6.66667	86	86	28.6667	0.18868	28.6667	0.18868
50	24	3	8	41	41	13.6667	0.36923	13.6667	0.36923
51	25	5	5	103	103	20.6	0.19531	20.6	0.19531
52	10	1	10	63	63	63	0.13699	63	0.13699
53	20	3	6.66667	13	13	4.33333	0.60606	4.33333	0.60606
54	25	3	8.33333	11	11	3.66667	0.69444	3.66667	0.69444
55	10	2	5	34	34	17	0.22727	17	0.22727
56	20	3	6.66667	98	98	32.6667	0.16949	32.6667	0.16949
57	30	5	6	121	121	24.2	0.19868	24.2	0.19868
58	45	8	5.625	42	42	5.25	0.51724	5.25	0.51724
59	45	9	5	14	14	1.55556	0.76271	1.55556	0.76271

60	5	0	*	0	0	*	1	*	1
61	0	0	*	0	0	*	0	*	0
62	5	1	5	57	57	57	0.08065	57	0.08065
63	5	0	*	0	0	*	1	*	1
64	15	3	5	49	49	16.3333	0.23438	16.3333	0.23438
65	47	8	5.875	16	16	2	0.74603	2	0.74603
66	11	1	11	30	30	30	0.26829	30	0.26829
67	15	3	5	5	5	1.66667	0.75	1.66667	0.75
68	50	5	10	36	36	7.2	0.5814	7.2	0.5814
69	10	0	*	0	0	*	1	*	1
70	5	0	*	52	52	*	1	*	1
71	10	1	10	51	51	51	0.16393	51	0.16393
72	40	7	5.71429	205	205	29.2857	0.16327	29.2857	0.16327
73	40	7	5.71429	60	60	8.57143	0.4	8.57143	0.4
74	15	2	7.5	10	10	5	0.6	5	0.6
75	0	0	*	0	0	*	0	*	0
76	0	0	*	0	0	*	0	*	0
77	0	0	*	0	0	*	0	*	0
78	0	0	*	0	0	*	0	*	0
79	0	0	*	0	0	*	0	*	0
80	0	0	*	0	0	*	0	*	0
81	5	0	*	0	0	*	1	*	1
82	25	5	5	101	101	20.2	0.19841	20.2	0.19841
83	10	0	*	0	0	*	1	*	1
84	30	5	6	19	19	3.8	0.61224	3.8	0.61224
85	5	0	*	0	0	*	1	*	1
86	20	4	5	67	67	16.75	0.22989	16.75	0.22989
87	10	0	*	0	0	*	1	*	1
88	20	3	6.66667	110	110	36.6667	0.15385	36.6667	0.15385
89	0	0	*	0	0	*	0	*	0
90	5	0	*	0	0	*	1	*	1
91	0	0	*	0	0	*	1	*	1
92	10	1	10	94	94	94	0.09615	94	0.09615
93	5	0	*	0	0	*	1	*	1

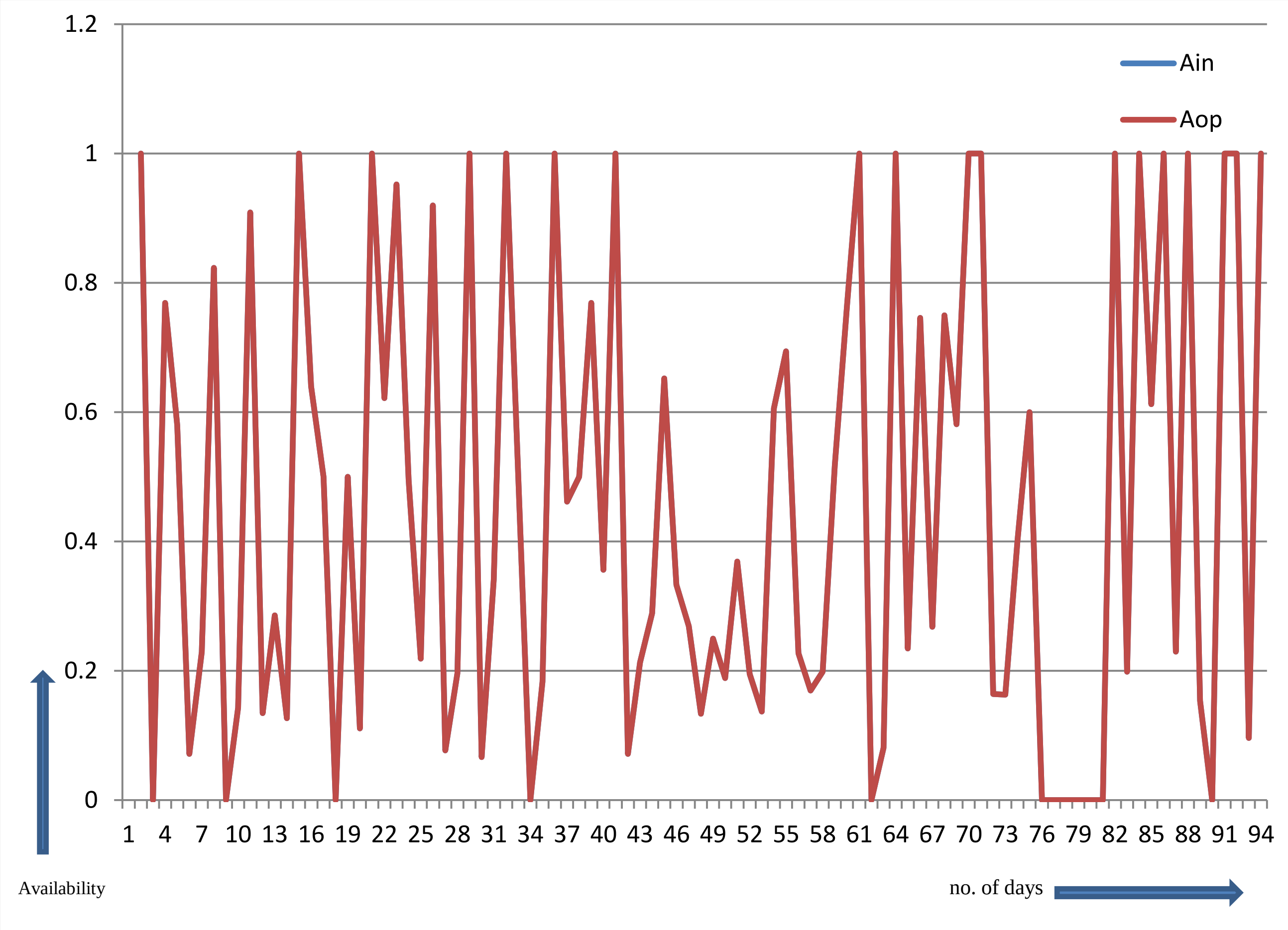


Figure 5.40: Availability of component 3

Table 5.15: Estimation of availability of sub-component 1

No. of Days	Operational time (in minute)	Failure no	MTBF	Down time (in minute)	Repair time (in minute)	MTTR	Ain	MDT	Aop
1	10	5	2	81	81	16.2	0.10989	16.2	0.10989
2	20	9	2.22222	52	52	5.77778	0.27778	5.77778	0.27778
3	10	4	2.5	12	12	3	0.45455	3	0.45455
4	40	18	2.22222	69	69	3.83333	0.36697	3.83333	0.36697
5	6	3	2	30	30	10	0.16667	10	0.16667
6	18	8	2.25	72	72	9	0.2	9	0.2
7	24	11	2.18182	46	46	4.18182	0.34286	4.18182	0.34286
8	21	9	2.33333	70	70	7.77778	0.23077	7.77778	0.23077
9	34	16	2.125	93	93	5.8125	0.26772	5.8125	0.26772
10	16	7	2.28571	43	43	6.14286	0.27119	6.14286	0.27119
11	36	18	2	71	71	3.94444	0.33645	3.94444	0.33645
12	12	5	2.4	28	28	5.6	0.3	5.6	0.3
13	30	13	2.30769	195	195	15	0.13333	15	0.13333

14	20	9	2.22222	58	58	6.44444	0.25641	6.44444	0.25641
15	10	4	2.5	14	14	3.5	0.41667	3.5	0.41667
16	20	9	2.22222	96	96	10.6667	0.17241	10.6667	0.17241
17	12	5	2.4	60	60	12	0.16667	12	0.16667
18	36	15	2.4	81	81	5.4	0.30769	5.4	0.30769
19	22	10	2.2	85	85	8.5	0.20561	8.5	0.20561
20	22	9	2.44444	17	17	1.88889	0.5641	1.88889	0.5641
21	24	11	2.18182	67	67	6.09091	0.26374	6.09091	0.26374
22	14	6	2.33333	60	60	10	0.18919	10	0.18919
23	40	19	2.10526	88	88	4.63158	0.3125	4.63158	0.3125
24	16	6	2.66667	85	85	14.1667	0.15842	14.1667	0.15842
25	28	13	2.15385	93	93	7.15385	0.2314	7.15385	0.2314
26	18	8	2.25	41	41	5.125	0.30508	5.125	0.30508
27	16	7	2.28571	12	12	1.71429	0.57143	1.71429	0.57143
28	24	11	2.18182	77	77	7	0.23762	7	0.23762
29	16	7	2.28571	51	51	7.28571	0.23881	7.28571	0.23881
30	26	12	2.16667	62	62	5.16667	0.29545	5.16667	0.29545
31	22	10	2.2	62	62	6.2	0.2619	6.2	0.2619
32	24	11	2.18182	48	48	4.36364	0.33333	4.36364	0.33333
33	24	11	2.18182	96	96	8.72727	0.2	8.72727	0.2
34	10	4	2.5	54	54	13.5	0.15625	13.5	0.15625
35	24	11	2.18182	27	27	2.45455	0.47059	2.45455	0.47059
36	20	9	2.22222	55	55	6.11111	0.26667	6.11111	0.26667
37	36	17	2.11765	132	132	7.76471	0.21429	7.76471	0.21429
38	34	16	2.125	89	89	5.5625	0.27642	5.5625	0.27642
39	26	12	2.16667	56	56	4.66667	0.31707	4.66667	0.31707
40	20	9	2.22222	73	73	8.11111	0.21505	8.11111	0.21505
41	20	9	2.22222	89	89	9.88889	0.18349	9.88889	0.18349
42	18	8	2.25	34	34	4.25	0.34615	4.25	0.34615
43	18	8	2.25	36	36	4.5	0.33333	4.5	0.33333
44	22	10	2.2	94	94	9.4	0.18966	9.4	0.18966
45	46	21	2.19048	102	102	4.85714	0.31081	4.85714	0.31081
46	34	16	2.125	139	139	8.6875	0.19653	8.6875	0.19653
47	10	4	2.5	19	19	4.75	0.34483	4.75	0.34483
48	30	13	2.30769	51	51	3.92308	0.37037	3.92308	0.37037
49	28	12	2.33333	47	47	3.91667	0.37333	3.91667	0.37333
50	20	8	2.5	88	88	11	0.18519	11	0.18519
51	57	27	2.11111	116	116	4.2963	0.32948	4.2963	0.32948
52	34	14	2.42857	85	85	6.07143	0.28571	6.07143	0.28571
53	30	14	2.14286	66	66	4.71429	0.3125	4.71429	0.3125
54	14	6	2.33333	121	121	20.1667	0.1037	20.1667	0.1037
55	20	9	2.22222	64	64	7.11111	0.2381	7.11111	0.2381
56	30	14	2.14286	134	134	9.57143	0.18293	9.57143	0.18293
57	28	12	2.33333	118	118	9.83333	0.19178	9.83333	0.19178

58	121	47	2.57447	47	47	1	0.72024	1	0.72024
59	34	16	2.125	109	109	6.8125	0.23776	6.8125	0.23776
60	18	8	2.25	48	48	6	0.27273	6	0.27273
61	36	17	2.11765	104	104	6.11765	0.25714	6.11765	0.25714
62	68	34	2	83	83	2.44118	0.45033	2.44118	0.45033
63	58	27	2.14815	75	75	2.77778	0.43609	2.77778	0.43609
64	48	22	2.18182	44	44	2	0.52174	2	0.52174
65	60	24	2.5	50	50	2.08333	0.54545	2.08333	0.54545
66	52	24	2.16667	87	87	3.625	0.3741	3.625	0.3741
67	26	12	2.16667	92	92	7.66667	0.22034	7.66667	0.22034
68	36	16	2.25	83	83	5.1875	0.30252	5.1875	0.30252
69	78	37	2.10811	151	151	4.08108	0.34061	4.08108	0.34061
70	82	38	2.15789	91	91	2.39474	0.47399	2.39474	0.47399
71	62	29	2.13793	217	217	7.48276	0.22222	7.48276	0.22222
72	86	41	2.09756	148	148	3.60976	0.36752	3.60976	0.36752
73	24	12	2	96	96	8	0.2	8	0.2
74	28	13	2.15385	110	110	8.46154	0.2029	8.46154	0.2029
75	16	7	2.28571	71	71	10.1429	0.18391	10.1429	0.18391
76	22	10	2.2	30	30	3	0.42308	3	0.42308
77	12	5	2.4	34	34	6.8	0.26087	6.8	0.26087
78	0	0	*	0	0	*	0	*	0
79	0	0	*	0	0	*	0	*	0
80	0	0	*	0	0	*	0	*	0
81	14	7	2	93	93	13.2857	0.13084	13.2857	0.13084
82	32	15	2.13333	125	125	8.33333	0.20382	8.33333	0.20382
83	28	13	2.15385	129	129	9.92308	0.17834	9.92308	0.17834
84	37	16	2.3125	103	103	6.4375	0.26429	6.4375	0.26429
85	18	8	2.25	65	65	8.125	0.21687	8.125	0.21687
86	40	19	2.10526	99	99	5.21053	0.28777	5.21053	0.28777
87	20	9	2.22222	60	60	6.66667	0.25	6.66667	0.25
88	32	14	2.28571	66	66	4.71429	0.32653	4.71429	0.32653
89	14	6	2.33333	66	66	11	0.175	11	0.175
90	28	13	2.15385	116	116	8.92308	0.19444	8.92308	0.19444
91	20	9	2.22222	131	131	14.5556	0.13245	14.5556	0.13245
92	14	5	2.8	59	59	11.8	0.19178	11.8	0.19178
93	18	8	2.25	31	31	3.875	0.36735	3.875	0.36735

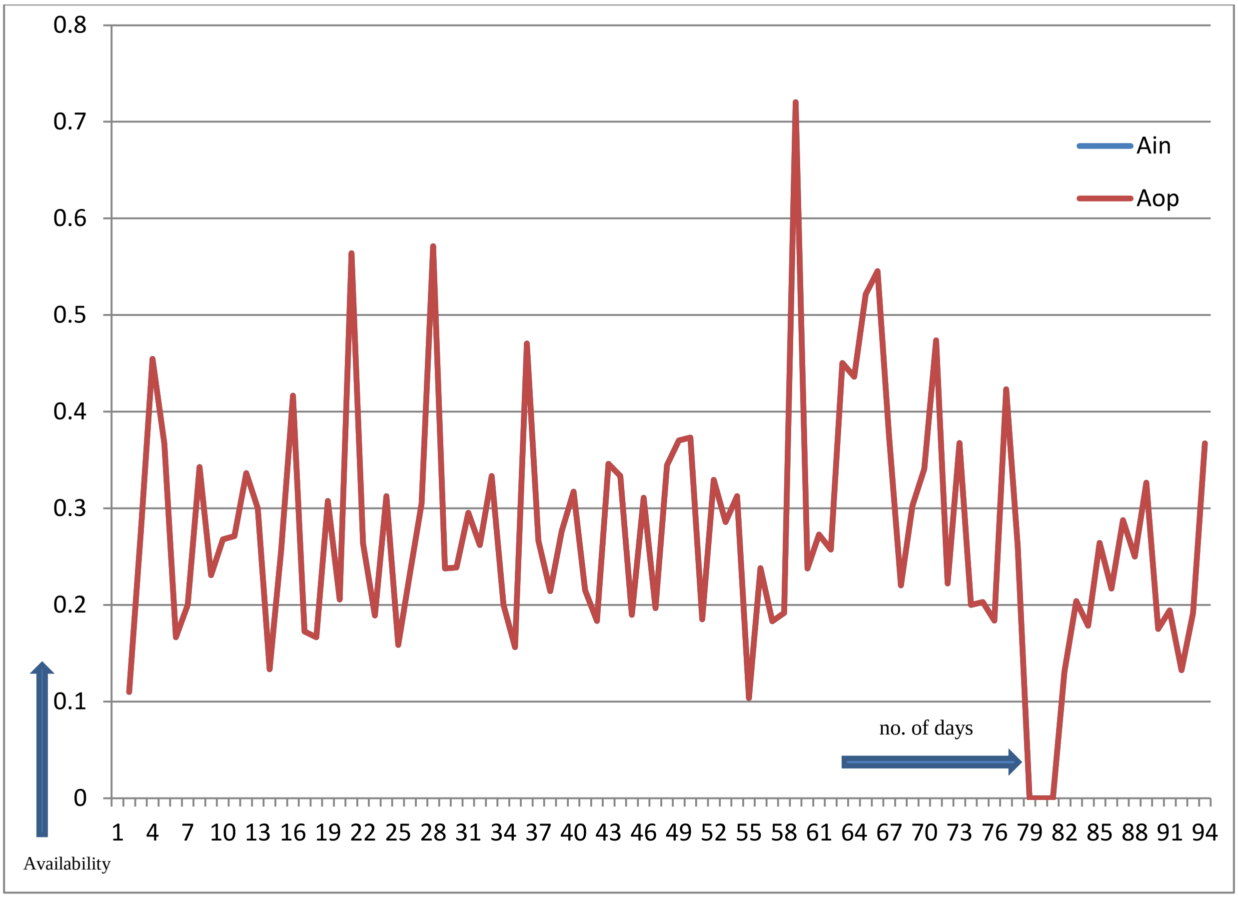


Figure 5.41: Availability of sub-component 1

Table 5.16: Estimation of availability of sub-component 2

No. of Days	Operational time (in minute)	Failure no	MTBF	Down time (in minute)	Repair time (in minute)	MTTR	Ain	MDT	Aop
1									
2	180	0	*	0	0	*	1	*	1
3	454	0	*	0	0	*	1	*	1
4	670	0	*	0	0	*	1	*	1
5	185	0	*	0	0	*	1	*	1
6	185	0	*	0	0	*	1	*	1
7	285	0	*	0	0	*	1	*	1
8	222	0	*	0	0	*	1	*	1
9	232	0	*	0	0	*	1	*	1
10	530	0	*	0	0	*	1	*	1
11	10	1	10	87	60	60	0.14286	87	0.10309
12	292	0	*	0	0	*	1	*	1
13	235	0	*	0	0	*	1	*	1
14	249	0	*	0	0	*	1	*	1
15	200	0	*	0	0	*	1	*	1

16	15	0	*	0	0	*	1	*	1
17	450	0	*	0	0	*	1	*	1
18	634	0	*	0	0	*	1	*	1
19	310	0	*	0	0	*	1	*	1
20	240	0	*	0	0	*	1	*	1
21	230	0	*	0	0	*	1	*	1
22	225	0	*	0	0	*	1	*	1
23	240	0	*	0	0	*	1	*	1
24	460	0	*	0	0	*	1	*	1
25	470	0	*	0	0	*	1	*	1
26	264	0	*	0	0	*	1	*	1
27	240	0	*	0	0	*	1	*	1
28	240	0	*	0	0	*	1	*	1
29	200	0	*	0	0	*	1	*	1
30	93	0	*	0	0	*	1	*	1
31	524	0	*	0	0	*	1	*	1
32	487	0	*	0	0	*	1	*	1
33	275	0	*	0	0	*	1	*	1
34	230	0	*	0	0	*	1	*	1
35	290	0	*	0	0	*	1	*	1
36	210	0	*	0	0	*	1	*	1
37	240	0	*	0	0	*	1	*	1
38	450	0	*	0	0	*	1	*	1
39	420	0	*	0	0	*	1	*	1
40	255	0	*	0	0	*	1	*	1
41	185	0	*	0	0	*	1	*	1
42	238	0	*	0	0	*	1	*	1
43	185	0	*	0	0	*	1	*	1
44	202	0	*	0	0	*	1	*	1
45	437	0	*	0	0	*	1	*	1
46	240	0	*	0	0	*	1	*	1
47	270	0	*	0	0	*	1	*	1
48	179	0	*	0	0	*	1	*	1
49	560	0	*	0	0	*	1	*	1
50	475	0	*	0	0	*	1	*	1
51	571	1	571	74	34	34	0.9438	74	0.88527
52	595	0	*	0	0	*	1	*	1
53	787	0	*	0	0	*	1	*	1
54	490	0	*	0	0	*	1	*	1
55	2	1	2	10	0	0	1	10	0.16667
56	2	1	2	210	210	210	0.00943	210	0.00943
57	570	0	*	0	0	*	1	*	1
58	216	0	*	0	0	*	1	*	1
59	612	0	*	0	0	*	1	*	1

60	480	0	*	0	0	*	1	*	1
61	262	0	*	0	0	*	1	*	1
62	423	0	*	0	0	*	1	*	1
63	320	0	*	0	0	*	1	*	1
64	760	0	*	0	0	*	1	*	1
65	1021	0	*	0	0	*	1	*	1
66	521	0	*	0	0	*	1	*	1
67	843	0	*	0	0	*	1	*	1
68	220	0	*	0	0	*	1	*	1
69	525	0	*	0	0	*	1	*	1
70	633	0	*	0	0	*	1	*	1
71	865	0	*	0	0	*	1	*	1
72	690	0	*	0	0	*	1	*	1
73	415	0	*	0	0	*	1	*	1
74	636	0	*	0	0	*	1	*	1
75	216	0	*	0	0	*	1	*	1
76	200	0	*	0	0	*	1	*	1
77	204	0	*	0	0	*	1	*	1
78	0	0	*	0	0	*	0	*	0
79	0	0	*	0	0	*	0	*	0
80	0	0	*	0	0	*	0	*	0
81	0	0	*	0	0	*	0	*	0
82	283	0	*	0	0	*	1	*	1
83	295	0	*	0	0	*	1	*	1
84	263	0	*	0	0	*	1	*	1
85	285	0	*	0	0	*	1	*	1
86	203	0	*	0	0	*	1	*	1
87	411	0	*	0	0	*	1	*	1
88	232	0	*	0	0	*	1	*	1
89	210	0	*	0	0	*	1	*	1
90	240	0	*	0	0	*	1	*	1
91	206	0	*	0	0	*	1	*	1
92	195	0	*	0	0	*	1	*	1
93	195	0	*	0	0	*	1	*	1

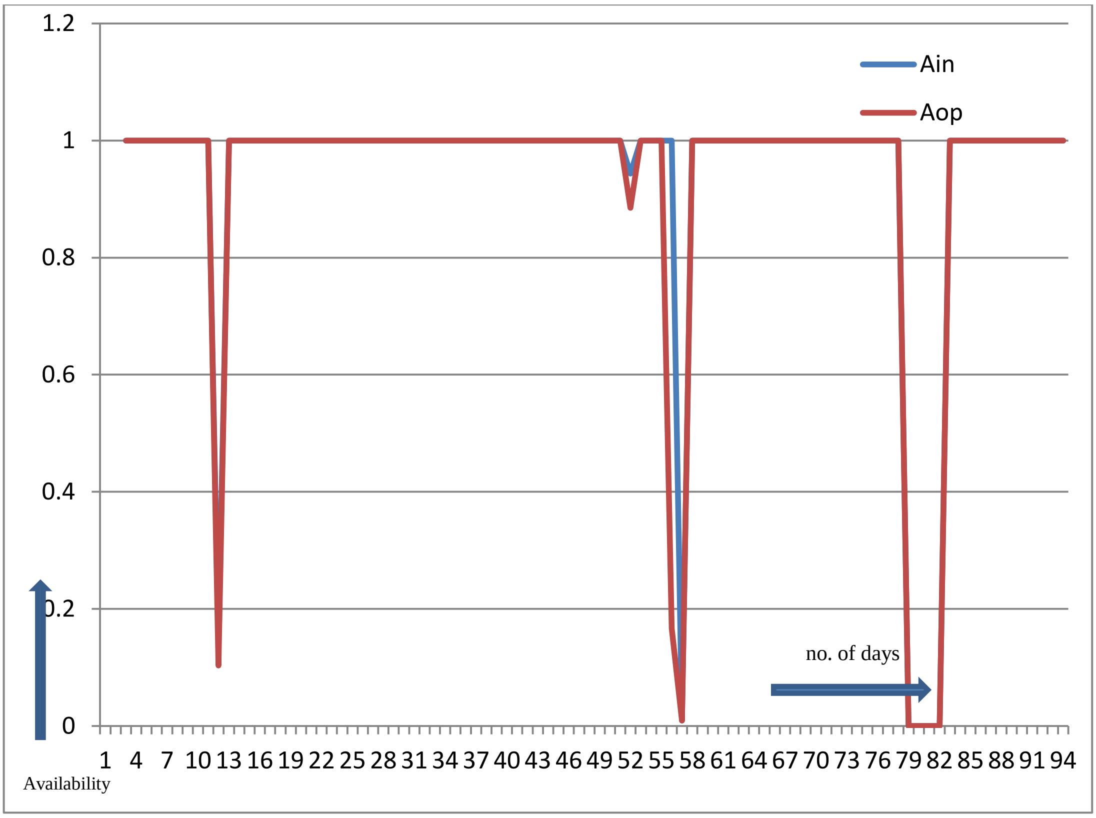


Figure 5.42: Availability of sub-component 2

5.8 Estimation of Production Loss Cost

This part of analysis is important for the estimation of Risk Index where 'MC' is representing maintenance cost and 'PLC' is representing production loss cost. PLC is given by:

PLC= DT*PL*SP ....(5.4)

Where 'DT' is Downtime, 'PL' is Production loss in impression per time and 'SP' is Selling price in rupees per impression. Downtime is associated with the failure data collected from the press. Selling price and maintenance cost are collected from the commercial section of the press. And finally the 'MC' & 'PLC' is tabulated in Table 5.17 & Table 5.18

Table 5.17: Estimation of maintenance cost of different components & sub-components

Sl. No.	Name of the Component	MC (in rupees)
C1	Printing machine	99275
C2	CTP 1	11790
C3	CTP 2	6440
SC1	Exposure unit	5240
SC2	Compressor	6400

Table 5.18: Estimation of production lost cost of different components & sub-components

Sl. No.	Name of the Component	PLC (in rupees)
C1	Printing machine	472956
C2	CTP 1	31687
C3	CTP 2	17116
SC1	Exposure unit	20303
SC2	Compressor	30409

5.9 Estimation of Consequence and Risk Index

This part of study deals with the estimation of consequence and risk index which are very much essential for maintenance planning. The important expressions for consequences and risk index [14, 93] are given below in equations 5.3, 5.4 & 5.5.

Consequence = MC + PLC ....(5.3)

Actual Risk (in rupees) = Failure Probability * Consequence ....(5.4)

Risk Index = Actual Risk / Acceptable Risk ....(5.5)

Considering acceptable risk criteria of Rs 180000 which is obtained from accounts department of the press Risk Index of different component & sub-component is shown in Table 5.19.

Table 5.19: Consequence, Risk and Risk Index of different components & sub-components

Sl. No.	Name of the Component	Consequence (in Rs)	Failure Probability	Actual Risk (in Rs)	**Risk Index**
C1	Printing machine	804251	0.553133696	444858.3281	2.47143516
C2	CTP 1	43477	0.735441421	31974.78665	0.17763333
C3	CTP 2	23556	0.538981219	12696.24159	0.07053468
SC1	Exposure unit	25543	0.776748064	19840.4758	0.11022487
SC2	Compressor	36809	0.177805814	6544.854208	0.03636030

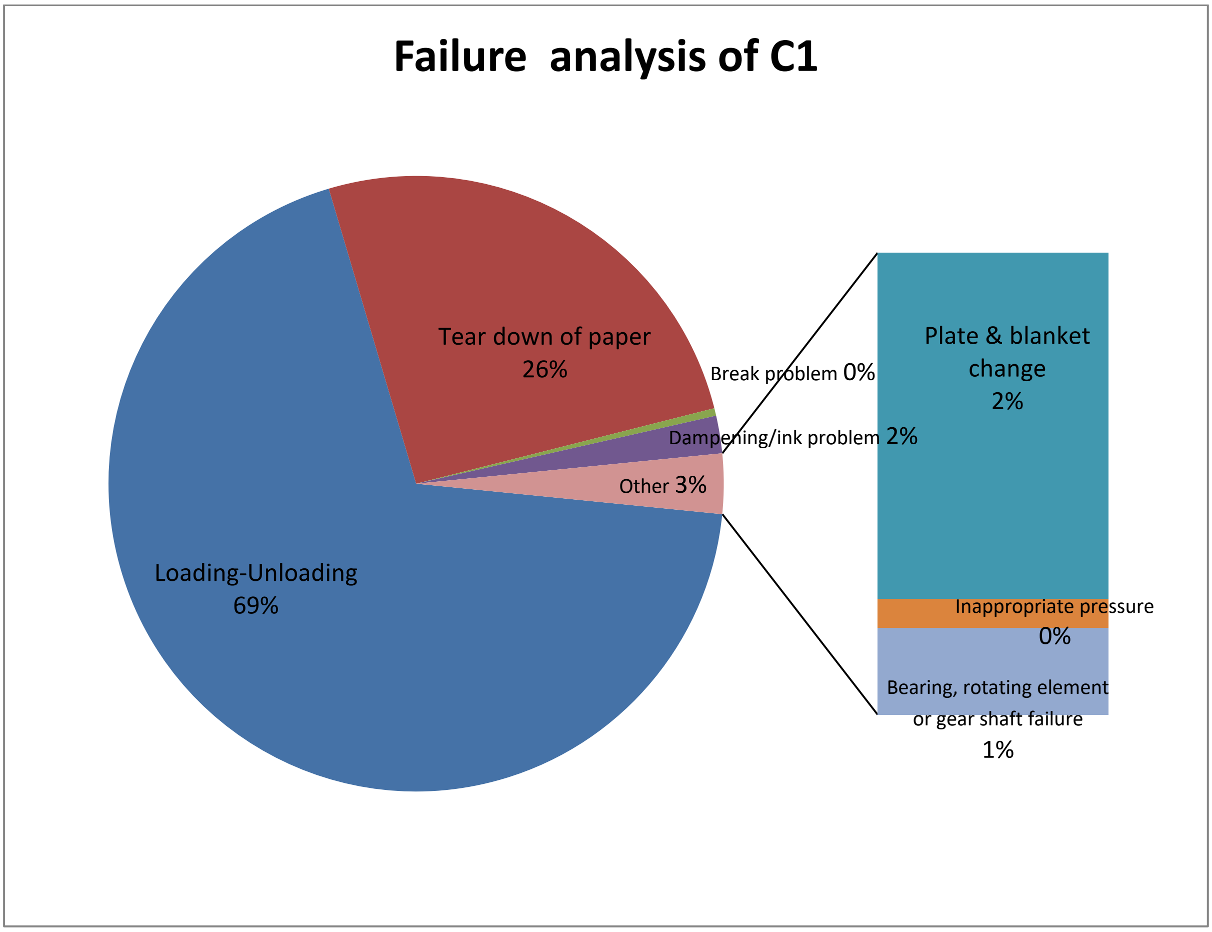
Now from the above table risk index of different component and sub-component is shown to understand the actual scenario. And further maintenance planning will be developed and the root cause of failure for the reduction of risk of the existing press should be analysed. It is also pertinent to mention that, initially it is seen that exposure unit is having highest failure rate but after risk analysis it is clear that main component i.e. component 1 (printing machine) of press is facing the maximum failure rate. It is also noteworthy to mention that loading unloading time for exposure unit is considered as the maximum breakdown time which is briefly described later.

5.10 Failure rate of different components & sub-components

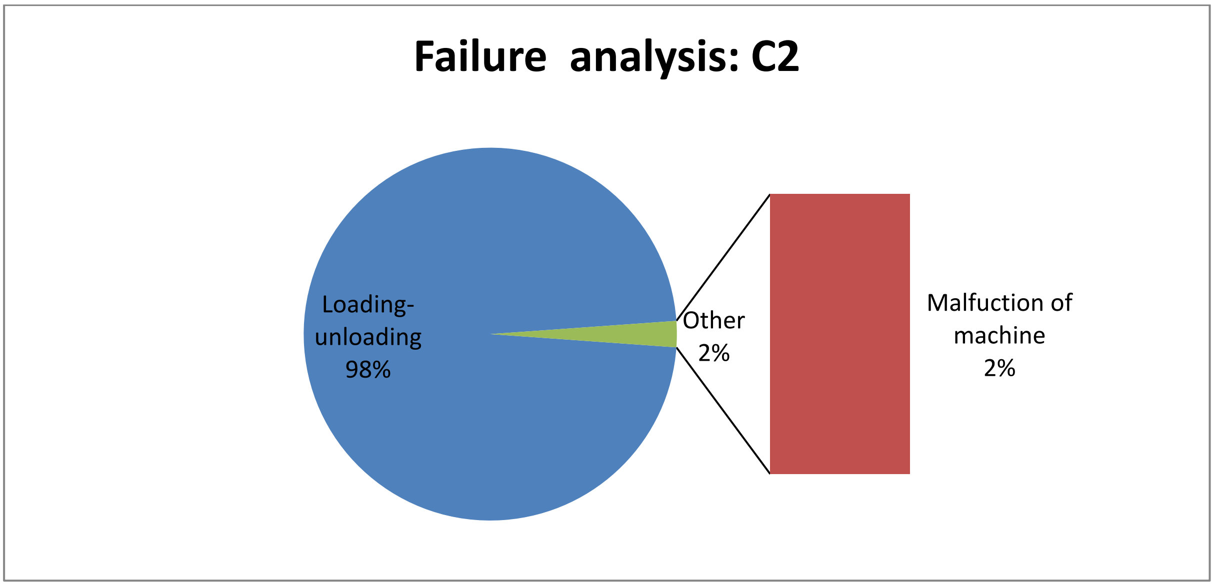
The types of failures for each component and subcomponent have been observed in the press and described in detail in Table 5.20 for further analysis. The percentage failures for each category of events of the selected components are also calculated. Figures 5.43 (a) – 5.43 (e) represent the corresponding Pie-charts of failure percentage occurred in the selected components.

Table 5.20: Failure rate of all components & sub-components

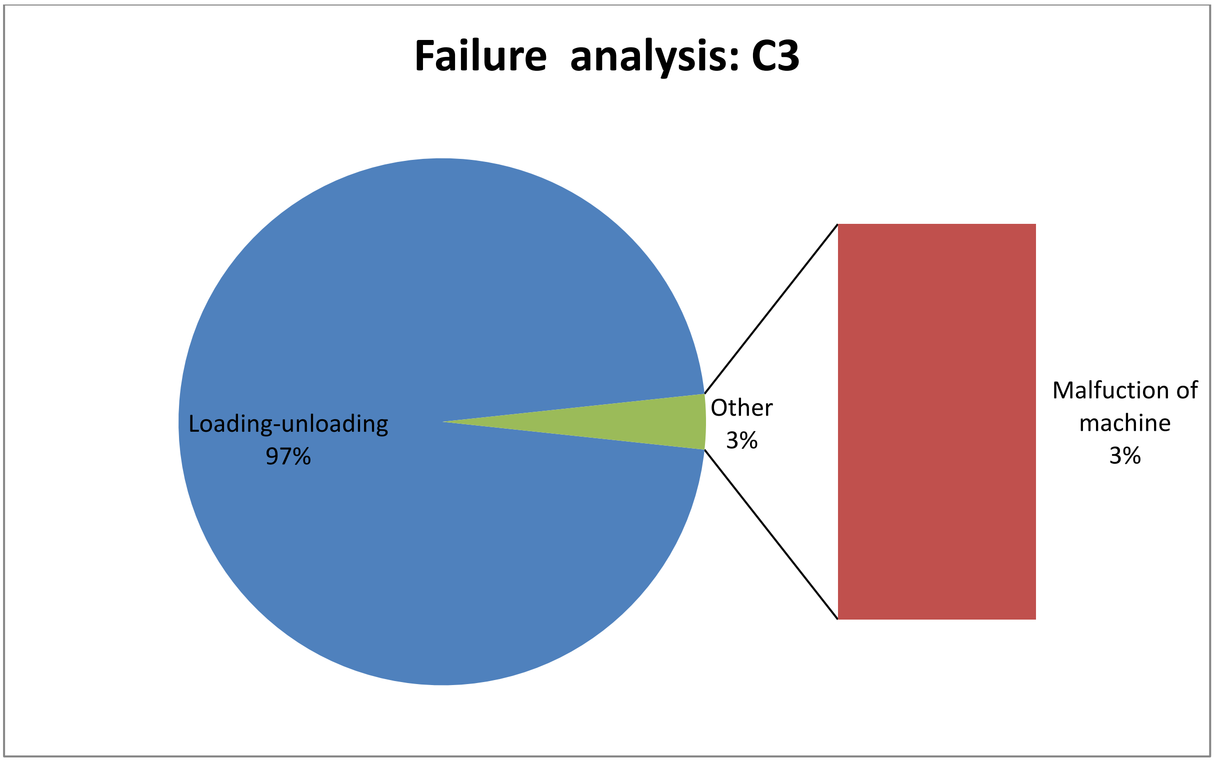
Component 1	**No of failure**	**Percentage**
Loading-Unloading	349	**68.83629191**
Tear down of paper	130	**25.64102564**
Break problem	2	**0.394477318**
Dampening/ink problem	10	**1.972386588**
Plate & blanket change	12	**2.366863905**
Inappropriate pressure	1	**0.197238659**
Bearing, rotating element or gear shaft failure	3	**0.591715976**
Total failure	**507**	
Component 2	**No of failure**	**Percentage**
Loading-unloading	692	**97.74011299**
Malfunction of machine	16	**2.259887006**
Total Failure	**708**	
Component 3	**No of failure**	**Percentage**
Loading-unloading	229	**96.62447257**
Malfunction of machine	8	**3.375527426**
Total Failure	**237**	
Sub-component 1	**No of failure**	**Percentage**
Loading-unloading	1109	**93.74471682**
Malfunction of machine	18	**1.521555368**
Delay of Exposing bulb lightening	56	**4.733727811**
Total Failure	**1183**	
Sub-component 2	**Failure Percentage**	
Excessive Load	**80**	
Valve leakage	**13**	
Oil ring/compressor ring failure	**7**	


Failure analysis of C1
Tear down of paper
26%
Break problem 0%
Dampening/ink problem 2%
Other 3%
Loading-Unloading
69%
Plate & blanket
change
2%
Inappropriate pressure
0%
Bearing, rotating element
or gear shaft failure
1%

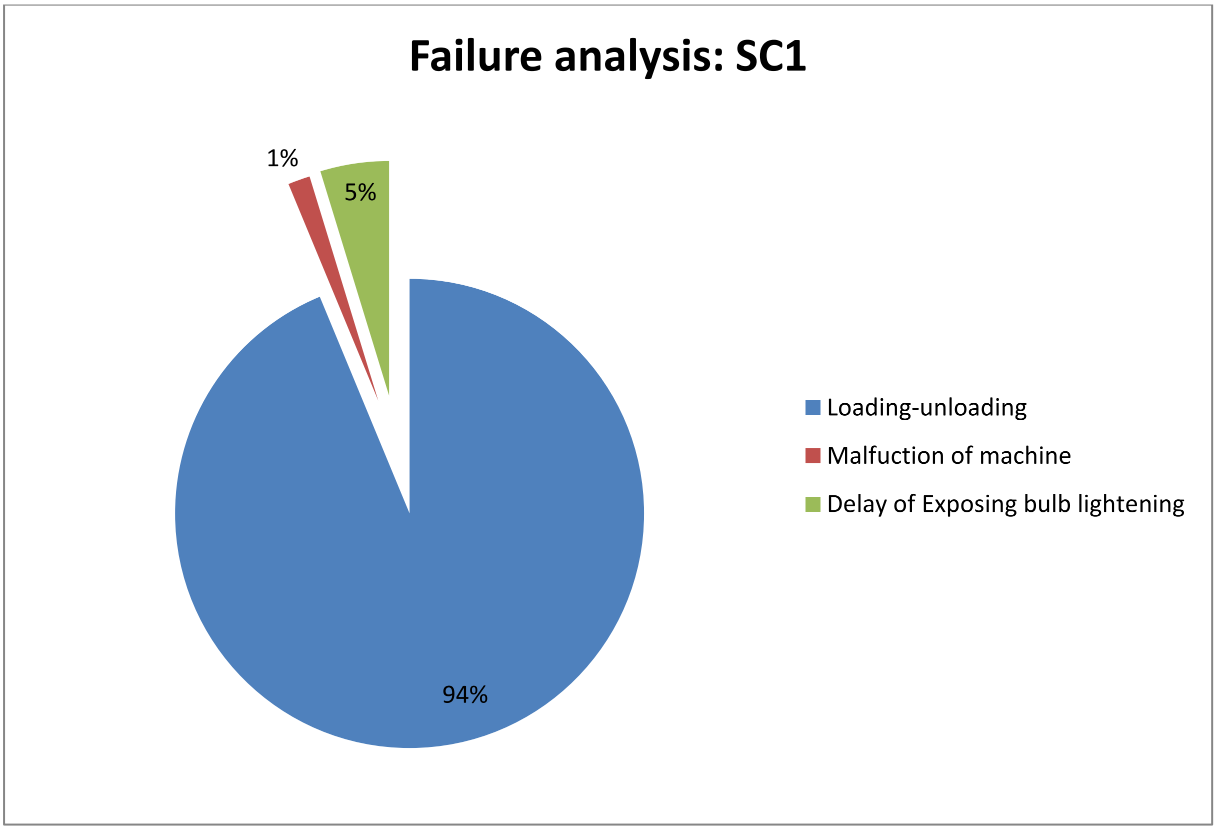
(a)


Failure analysis: C2
Loading-
unloading
98%
Other
2%
Malfuction of
machine
2%

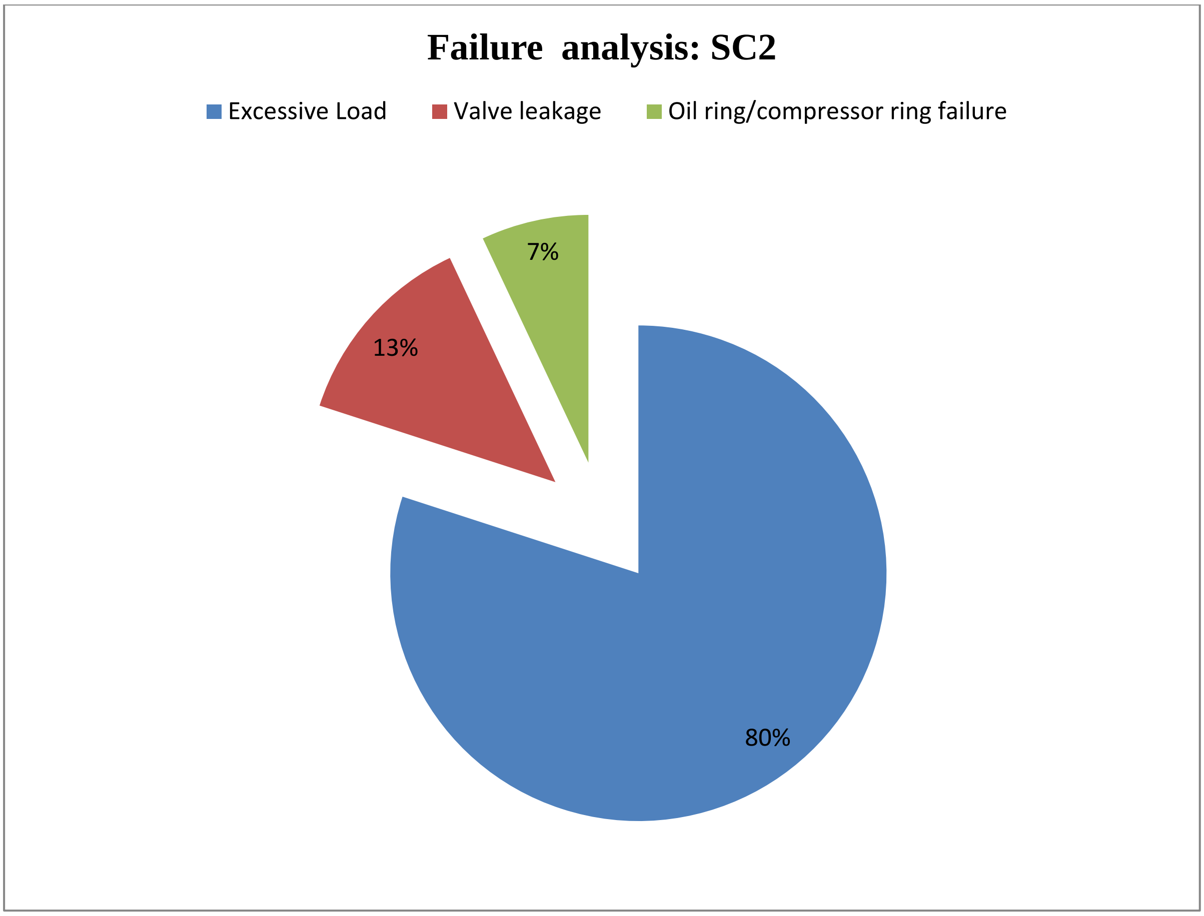
(b)


Failure analysis: C3
Loading-unloading
97%
Other
3%
Malfuction of
machine
3%

(c)


Failure analysis: SC1
1%
5%
94%
Loading-unloading
Malfuction of machine
Delay of Exposing bulb lightening

(d)



(e)

Figures 5.43: Failure analysis of (a) Component1, (b) Component2, (c) Component3, (d) Sub-component1 & (e) Sub-component2 in terms of Pie chart

5.11 Pareto analysis of different components & sub-components

Now the failures have been prioritized for the selected components. For this Pareto analysis has been done to understand the failure scenario. All types of failures are arranged in the Pareto chart according to the highest priority of failure. It helps to take decisions for providing correct maintenance planning to reduce the breakdown and risk index. Figures 5.44-5.48 represent the corresponding Pareto chart for different components & sub-components.

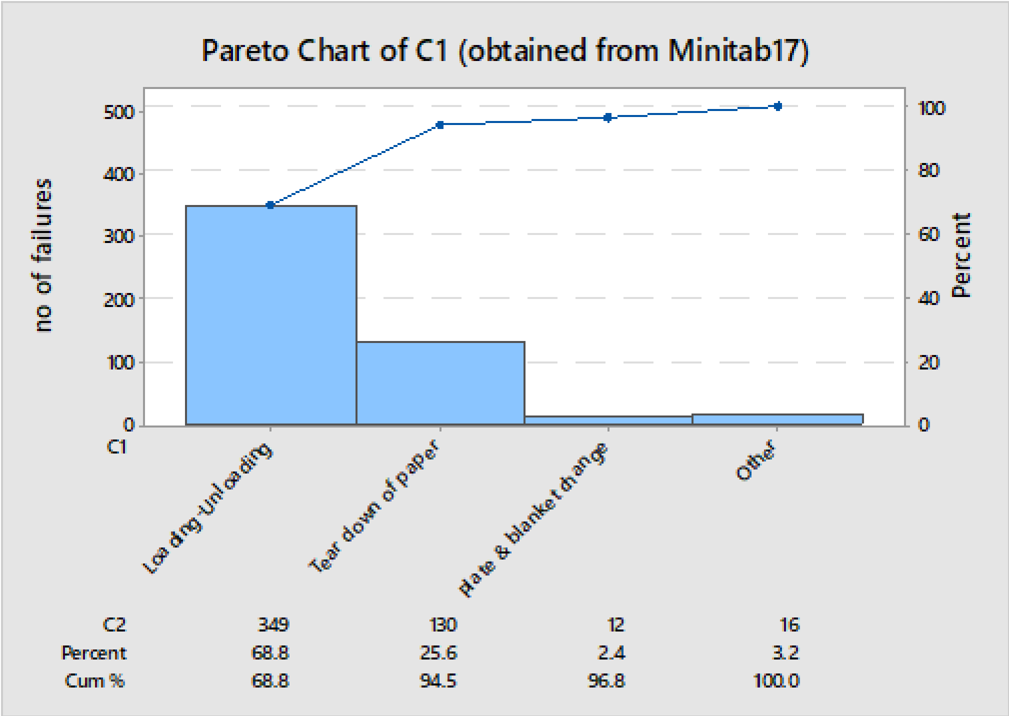


Figure 5.44: Pareto chart of components 1

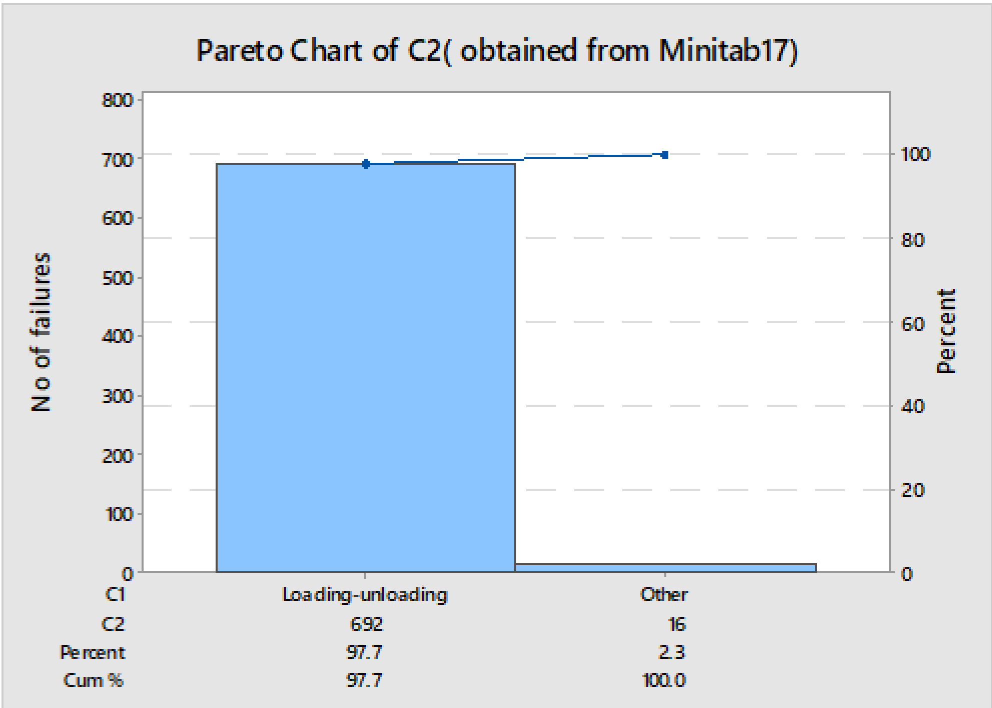


Figure 45: Pareto chart of components 2

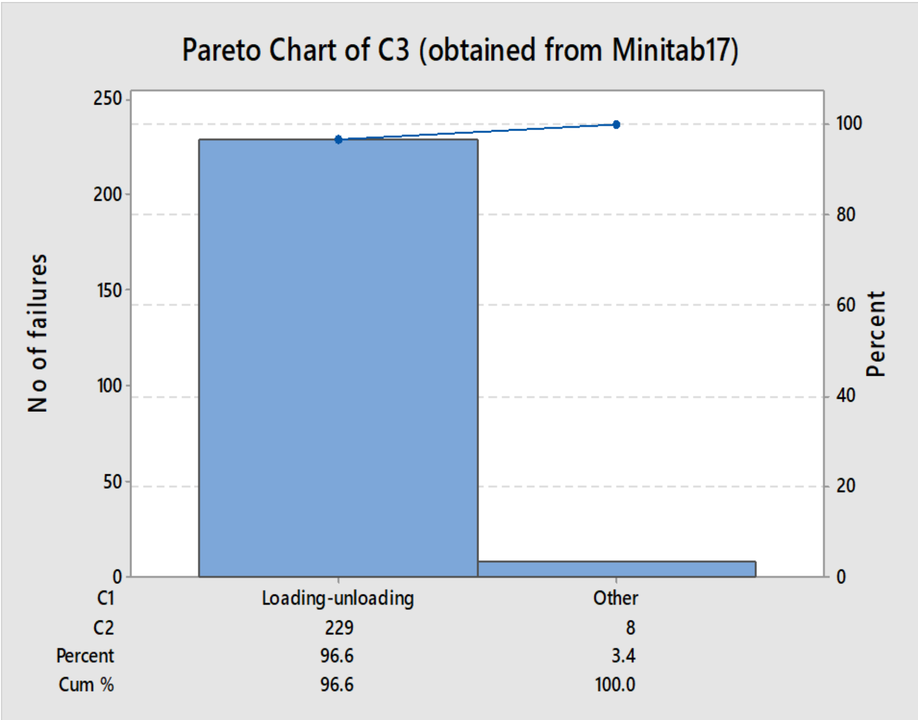


Figure 5.46: Pareto chart of components 3

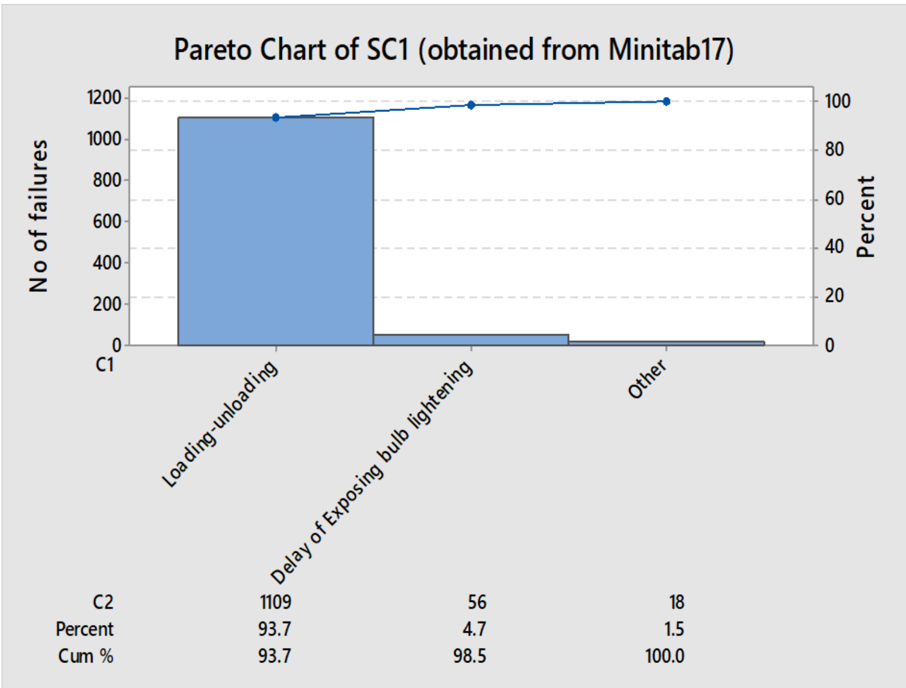


Figure 5.47: Pareto chart of sub-components 1

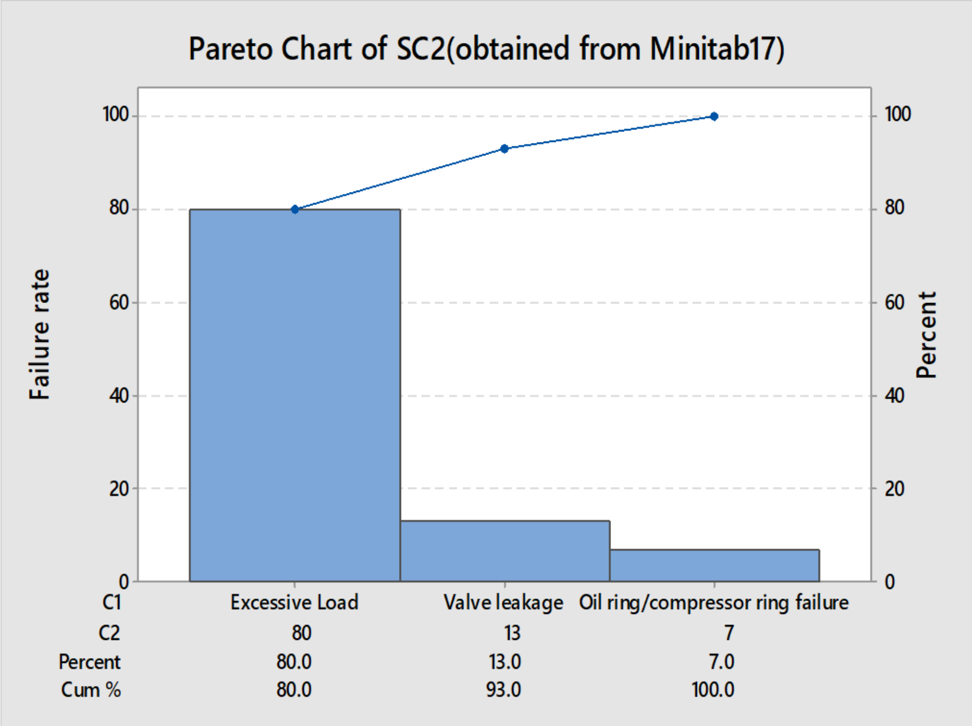


Figure 5.48: Pareto chart of sub-components 2

5.12 Fault Tree Analysis

Fault-Tree analysis (FTA) is widely used in reliability analysis and risk-based maintenance approaches [95]. Here different symbols are used to characterise the failure events. For example rectangle symbol represents the resultant event that results from the combination of fault or breakdown events through the input of logic gate. OR gate denotes that an output fault event occurs if one or more of the input fault events occur; circular symbol represents the basic fault or breakdown event etc.

From this concept FTA diagram is developed to understand the actual failure scenario where highest priority or high risk events are arranged from left side of the circuit as shown in Figure 5.49. The notations used for all types of selected components are described separately in Table 5.2, which are used in FTA analysis.

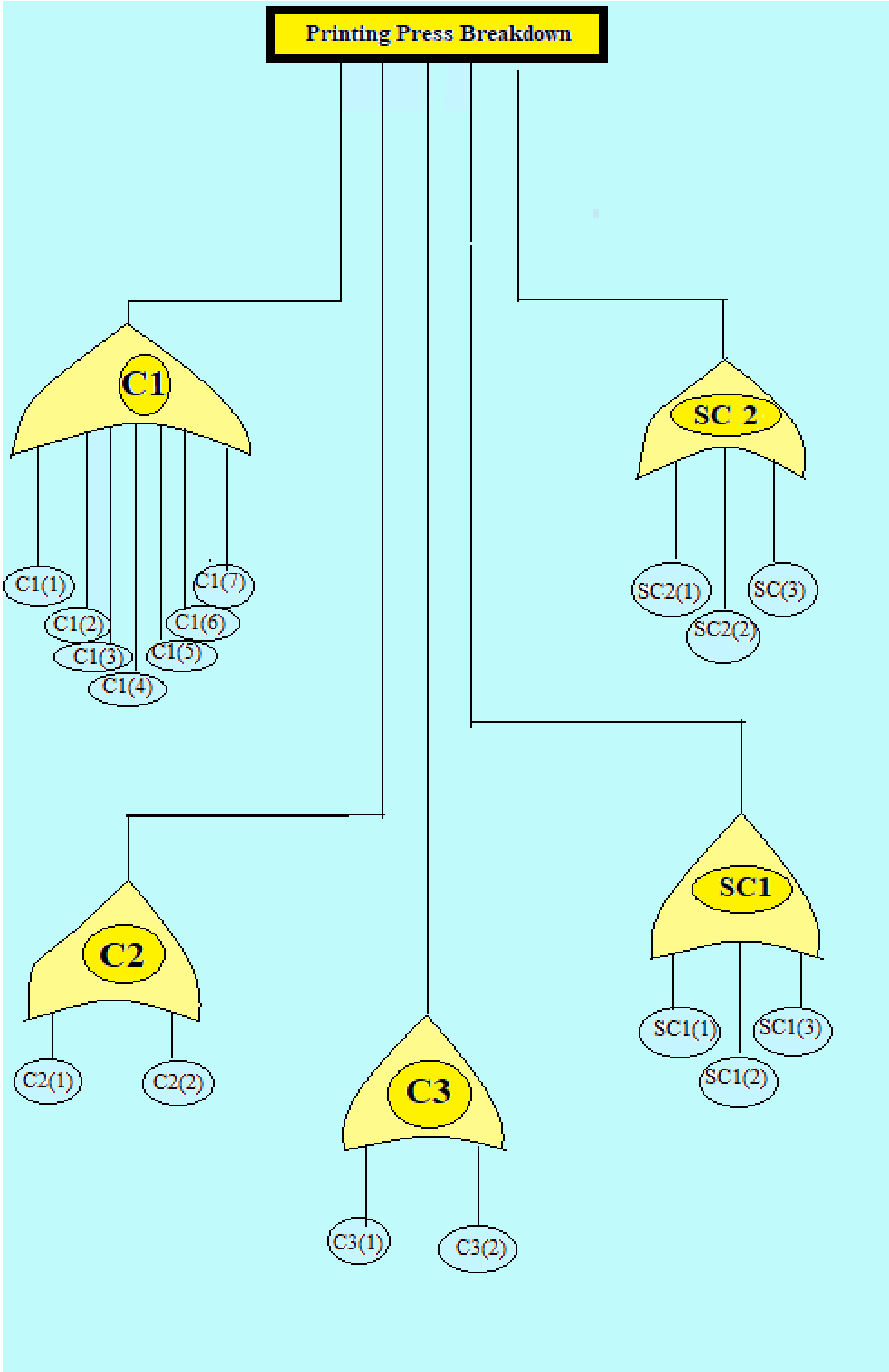


Figure 5.49: FTA diagram of the printing press

Table 5.21: Failure scenario of the printing press

Component / sub-component	Failure name	Failure no.	Risk Index	Grade of Risk with respect to R.I.	Notation of equipment	Notation for all types of failures of component / subcomponent
Printing machine			2.4143	**High**	C1	
	Loading-Unloading	349				C1(1)
	Tear down of paper	130				C1(2)
	Plate & blanket change	12				C1(3)
	Dampening/ink problem	10				C1(4)
	Bearing, rotating element or gear shaft failure	3				C1(5)
	Break problem	2				C1(6)
	Inappropriate pressure	1				C1(7)
CTP 1			0.1776	Low	C2	
	Loading-unloading	692				C2(1)
	Malfunction of machine	16				C2(2)
CTP 2			0.0705	Low	C3	
	Loading-unloading	229				C3(1)
	Malfunction of machine	8				C3(2)
Exposure unit			0.1102	Low	SC1	
	Loading-unloading	110 9				SC1(1)
	Malfunction of machine	18				SC1(2)
	Delay of Exposing bulb lightening	56				SC1(3)
Compressor			0.0363	Low	SC2	
	Excessive Load	80%				SC2(1)
	Valve leakage	13%				SC2(2)
	Oil ring/compressor ring failure	7%				SC2(3)

Chapter 6

RESULTS AND DISCUSSIONS

6.1 Introduction

In this chapter, reliability, availability and maintainability have been analysed and discussed with the help of considerable database collected for the present investigation. The database collected for the present investigation. The database collected and their corresponding analysis has been given earlier in chapter 4 and chapter 5. Weibull analysis and failure analysis for the components and subcomponents has been already been described for analysing the reliability. Here Cause & Effect diagram along with their remedial suggestions has been developed. Also risk analysis, Pareto analysis, Fault-Tree analysis have been made for further maintenance planning. To check the validity of the future maintenance planning, overall equipment effectiveness for selected component has been measured. Overall performance of each components has been analysed by using Time-Motion study.

6.2 Risk Index of different components & sub-components of press

A comprehensive picture of risk of different components of the Printing Press can be viewed from the failures of different components and subcomponents. The risk depends on the consequence of failures. Risk Index (R.I.) obtained earlier in Art. 5.9 determine the severity of failure or priority of maintenance of the components and subcomponents of the printing press. The Risk Index along with their level of concern of different components and subcomponents are shown in Table 6.1. Generally components and subcomponents are divided into three categories viz: High Risk (R.I. value is greater than 0.8), Medium Risk (R.I. value is in between 0.4 to 0.8) and Low Risk (R.I. value is less than 0.4). Here in this study one component is observed of high risk and that is component 1 (printing machine).

Table 6.1: Risk Index (RI) of different components & subcomponents with level of concern

Sl. No.	Name of the Component	Actual Risk (in Rs.)	**Risk Index**	Level of Concern
C1	Printing machine	444858.3281	2.47143516	**HIGH**
C2	CTP 1	31974.78665	0.17763333	LOW
C3	CTP 2	12696.24159	0.07053468	LOW
SC1	Exposure unit	19840.4758	0.11022487	LOW
SC2	Compressor	6544.854208	0.036360301	LOW

Now, on the basis of above Table 6.1, graphical representation of actual risk scenario (in rupees) and risk index scenario is drawn in the form of Pie chart and Bar chart shown in Figure 6.1 & 6.2 for better understanding the exact situation of risk in "Printing press".

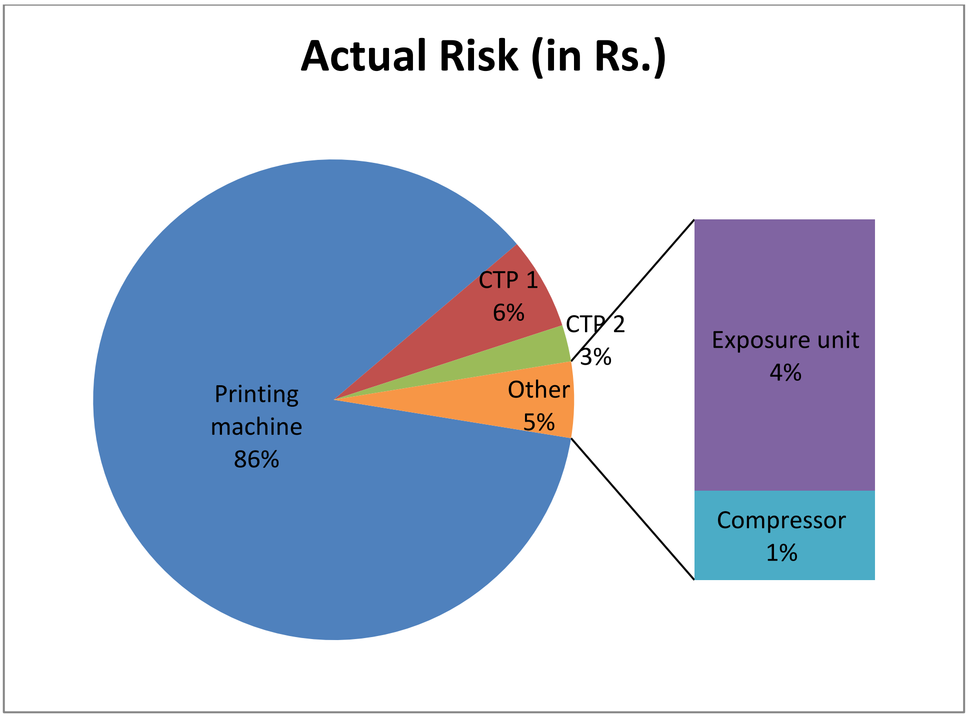


Figure 6.1: Actual risk (in terms of rupees) of different Components & sub-components

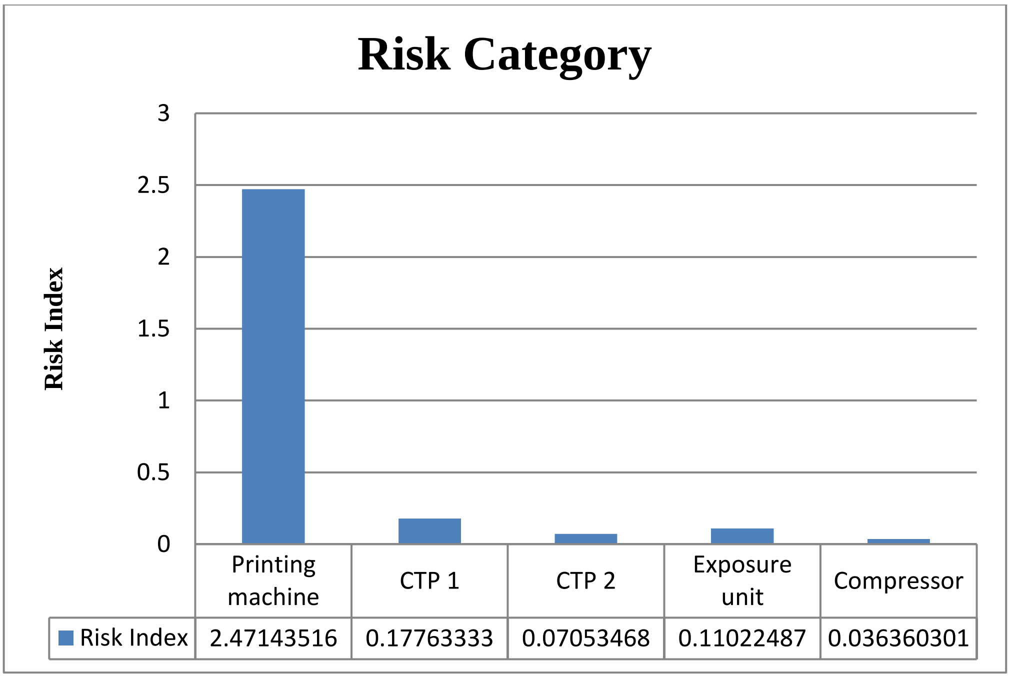


Figure 6.2: Risk category of different components & Sub-component

6.3 Reliability Estimation

Failure probability and reliability of the printing press have been estimated earlier shown in Art. 5.6. It is easy to understand the possible failure mechanism and their causes of failures (which are also listed previously in Art. 3.9, Table 3.2) as the reliability estimation of different components of the press provides the values of shape parameter (β) and mean time to failure (MTTF) which are given earlier in Figure 5.11, 5.15, 5.19, 5.23 & 5.27. Now for ready reference, reliability of the components and subcomponents are listed in Table 6.2 which are developed from the corresponding Weibull diagram. Therefore, it is observed that the reliability of different components and subcomponents are in the range of 22.32% to 82.21%. The reliability of the compressor (SC2) is maximum (82.21%) whereas the reliability of the exposure unit (SC1) and CTP1 (C2) is minimum as shown in Table 6.2. All the other components have a moderate reliability.

Table 6.2: Reliability of different components & sub-components of Printing Press

Sl. No.	Name of the Component	Shape parameter (obtained from Weibull) (β)	MTTF (obtained from Weibull) (in minute)	Reliability (in %)
1	Printing machine(C1)	1.83997	252.068	44.68663041
2	CTP 1(C2)	1.95228	38.1403	26.45585792
3	CTP 2(C3)	1.74803	35.978	46.10187813
4	Exposure unit(SC1)	1.72513	41.3592	22.32519361
5	Compressor(SC2)	0.406208	135.967	82.2194186

6.4 Availability of different components of the printing press

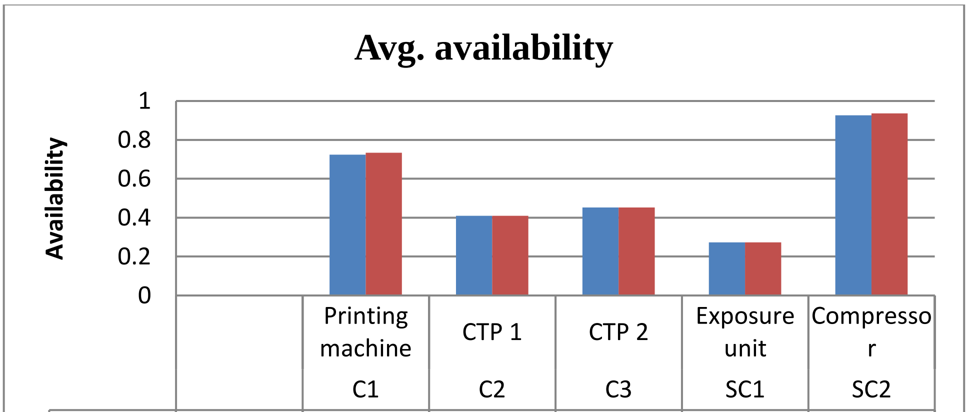
As per the definition of inherent and operational availability that are discussed in Art. 3.4 & 5.7, the availability is calculated for three months (which is tabulated earlier in Tables 5.12 – 5.16) and drawn which are shown in Figures 5.38 - 5.42. After that average inherent & operational availability are calculated and given in Table 6.3).

Table 6.3: Estimated maximum availability of printing press

Name of component / subcomponent	Avg. Operational Availability	Avg. Inherent Availability
Printing machine (C1)	0.724290926	0.73380371
CTP 1 (C2)	0.410538322	0.41053832
CTP 2 (C3)	0.452031175	0.45203118
Exposure unit (SC1)	0.273912469	0.27391247
Compressor (SC2)	0.925700704	0.9358271

Figures 5.39, 5.40 & 5.41 show that CTP1, CTP2 and Exposure unit undergoes preventive maintenance & overhauling for some time during three months as both inherent & operational availability are almost coinciding with each other. It is important to note that in both type of availability of the exposure unit (SC2) possess low availability and this is because that the loading and unloading have been considered as failure. The consideration of this breakdown is clearly discussed in Art. 5.10. Whereas Figures 5.38 & 5.42 show that the printing machine and compressor undergoes preventive maintenance & overhauling for some time during three months as both the inherent & operational availability are close with each other.

Figure 6.3 represents the bar diagram of availability of different components for comparison of the values of availability.



	Printing machine C1	CTP 1 C2	CTP 2 C3	Exposure unit SC1	Compressor SC2
Avg Aop	0.7242909	0.4105383	0.4520312	0.2739125	0.9257007
Avg Ain	0.7338037	0.4105383	0.4520312	0.2739125	0.9358271

Figure 6.3: Bar diagram of various availability of printing press

6.5 Analysis of failure rates of different components & sub-components

It is observed in Art. 5.10 that for components C1, C2, C3 and subcomponent SC1 loading unloading is considered as failure due to stoppage of the equipment or machine and for the main printing machine (i.e. C1) it has also specific stoppage or breakdown time. Hence, for C1 Tear down of paper possess 2nd highest percentage of breakdown with respect to other breakdowns like break problem, dampening or ink problem, plate & blanket change due to angle or disorientation during fixation, inappropriate pressure of bearing, rotating element or gear shaft failure.

CTP machines (i.e. C2 & C3) faced minor problem of malfunction of machine otherwise rest of the failures are due to loading unloading as shown in Table 5.20. For exposure unit (SC1), only 1.5% and 4.7% of the breakdown are due to malfunction of machine and delay in exposing of plate by the lightening of bulb. Remaining 93.7% of breakdowns for SC1 are due to loading unloading of material or plate. It is also observed that the compressor (SC2) is experiencing excessive load. It is seen that only 13% & 7% of overall failure are considered as breakdowns due to valve leakage problem and oil ring/compressor ring failure.

6.6 Analysis of the major causes of failures and recommendations for their remedies

In this article different types of failures and their root causes are studied by Cause & Effect diagram, Pareto analysis and Fault Tree analysis. Also their corresponding remedies are suggested to reduce these failures.

6.6.1 Cause-and-Effect diagram of different components & sub-components

The cause & effect diagram is also known as Fish Bone diagram or Ishikawa diagram or analysis which is composed of five main pillars namely Manmade, Machines, Method, Environment & Material. These causes lead to the main effects of failure i.e. breakdown of a printing press. Each pillar also has sub reasons which are called branches and again each branch are subdivided into different sub-branches that leads to the causes of breakdown of each component and subcomponent of the press. Figure 6.4 gives the complete overview of the causes of breakdown of components and subcomponents of the press.

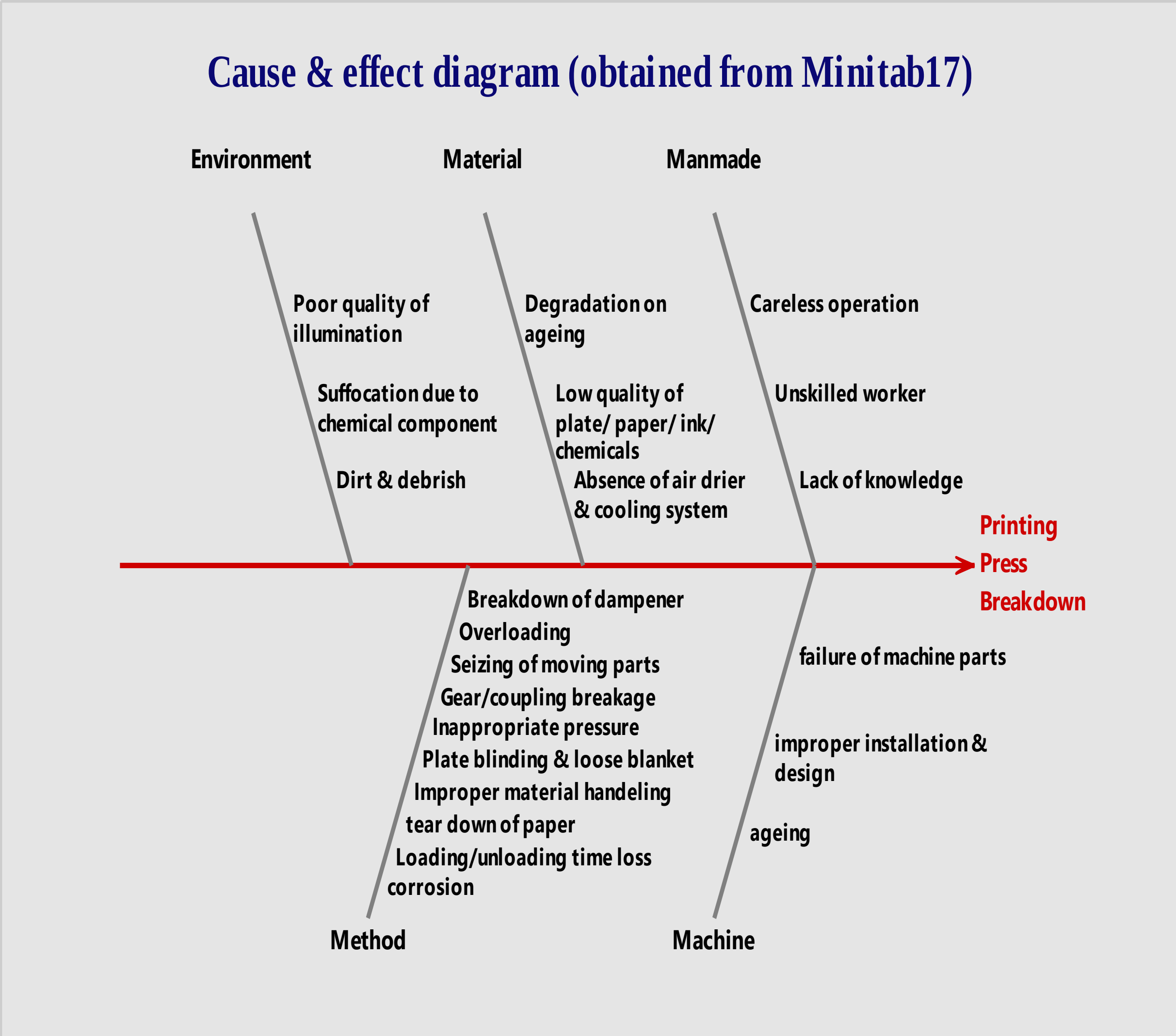


Figure 6.4: Fish Bone diagram or Cause & Effect diagram

The reason for improper functioning arises from the Cause & Effect diagram is listed and the recommended preventive measure to be taken and has been suggested in Table 6.4.

Table 6.4: Different types of failures and their corresponding recommendation

Component/ sub-component	Causes	Corrective Actions	Recommendation for Maintenance Approach
Printing machine (C1)	Loading- Unloading	Automation	Breakdown Maintenance
	Tear down of paper, dampening & ink problem, inappropriate pressure	Continuous monitor on the given task or job to arise failure	Corrective Maintenance
	Brake problem	Repair	Breakdown Maintenance
	Bearing, rotating element or	Repair	Breakdown

	gear shaft failure		Maintenance
	Failure due to plate & blanket	If misprint occurs due to angle of plate or disorientation of plate then replace the plate. Remake the plate again. On ageing of machine, degradation or loosening of blanket observed. Pretension of blanket or incorrect installation of blanket need proper repair	Corrective & Preventive Maintenance
CTP1 (C2)	Loading- Unloading	Automation	Breakdown Maintenance
	Delay of printing due to malfunction machine	Detection of root cause of failure	Predictive Maintenance
CTP2 (C3)	Loading- Unloading	Automation	Breakdown Maintenance
	Delay of printing due to malfunction machine	Detection of root cause of failure	Predictive Maintenance
Exposure unit (SC1)	Loading- Unloading	Automation	Breakdown Maintenance
	Delay of exposure of due to malfunction of machine or exposing bulb	Replace or repair lightening system & detection of source of malfunction of machine.	Preventive or Breakdown & Proactive Maintenance
Comporessor1 (SC2)	An excessive load, inappropriate design, not maintaining the Thermodynamics law causes valve or lead breakage or leakage	Load reduction, redesign, maintain Thermodynamics law	Predictive Maintenance
	Oil ring/compression ring failure	Repair or replace	Breakdown or Preventive Maintenance

6.6.2 Pareto analysis of different failures of all the components & sub-components

Now, on the basis of Table 5.20, Pareto analysis has been conducted by MINITAB17 for different failures of all the components and subcomponents which are shown from Figure 5.44 to Figure 5.48 where failures have been prioritized for the selected components on the basis of percentage failure. It is seen that not only number of failures of the individual machine is considered but also the percentage along with their cumulative percentage of failure have been shown for the ease of analysis and realization of failure scenarios. Finally it helps to indicate on the high priority of failures so that necessary steps can be implemented to overcome the failures.

6.6.2.1 Overall Pareto analysis

In this article, Pareto analysis of all the components and subcomponents has been drawn on the basis of Risk Index (R.I.). Level of Risk is already discussed in Art. 6.2. On the basis of risk level, rank of the priority for Maintenance Planning is considered and given in Table 6.5. Figure 6.5 describes the overall Pareto analysis of all the components and subcomponents. Which equipment is needed to be chosen for maintenance planning is decided from this Pareto analysis.

Table 6.5: Ranking of Risk Indices of different components

Sl. No.	Component/ sub-component	Risk Index	**Level of Concern**	Rank of priority
C1	Printing machine	2.47143516	**High**	**A**
C2	CTP 1	0.17763333	Low	C
C3	CTP 2	0.07053468	Low	C
SC1	Exposure unit	0.11022487	Low	C
SC2	Compressor	0.036360301	Low	C

It is clear from the Table 6.5 and Figure 6.5 that component 1 (printing machine) is needed to be chosen first for further maintenance planning due to its high Risk Index for the reduction of risk.

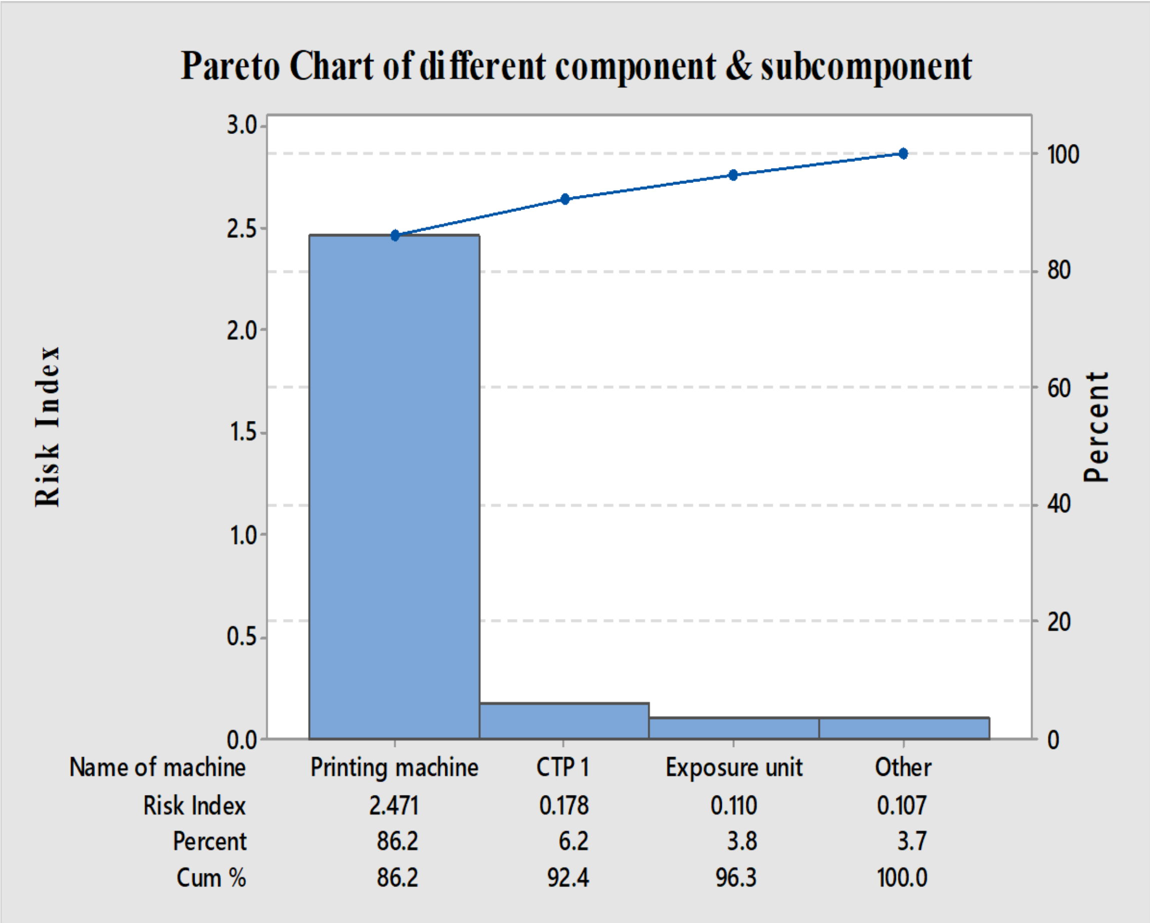


Figure 6.5: Overall Pareto analysis of different components & subcomponents

6.6.3 Failure Tree Analysis

Just like Pareto analysis, Failure Tree Analysis (FTA) is done earlier in Art. 5.12. It is also important to note that FTA is done with the help of brainstorming session. Several breakdown or causes of breakdowns are shown as a logic which are connected to logic OR gate. It means that if any of the failure occurs then the component or subcomponent will face breakdown. It is also important to note that high priority failure are arranged from the left side of the logic diagram. When all the logic gate diagram is drawn then they are again arranged from left side and finally connected to the Printing press breakdown which is symbolised by rectangular shape. FTA is also important for maintenance planning as it indicates which equipment is considered as the next under maintenance action.

6.7 Overall Equipment Effectiveness

Overall Equipment Effectiveness (OEE) of the component is measured on the basis of high risk. Here component 1 is at high risk thus OEE of component 1 is only calculated here. Table 6.6 shows the different losses that are described in Art 3.13 where percentage of availability loss is 76.6%, performance loss is 97.5% and quality loss is 98.7%. These losses have been calculated by using Equation 3.22, 3.23 and 3.24 (given earlier in Chapter 3). Also the data for determining the above losses are given in Table 6.6 are calculated from the basic data given in Chapter 4 and used for measuring OEE. From this calculated losses the overall effectiveness of the equipment for component 1 (i.e. printing machine) is determined and found to be 57.26%. It indicates that this component requires further maintenance planning for improvement.

Table 6.6: OEE of the Component 1

Observation time(in min)	20472
Planned production time (in min)	19436
Planned downtime(in minute)	1036
Unplanned downtime (in minute)	4539
Operating time	14886
Actual production Output	7737591
Capacity per given time(in min)	687/min
Expected output	10226682
Amount defect & reproduced	96364
Availability loss	0.766464293
Performance loss	0.756608155
Quality loss	0.987545995
OEE	0.572690893

6.8 Time motion study (TMS) of different components & sub-components

Time motion study is performed for analysing the performance of the components. Here in the present work time motion study has been done on the daily basis of the production unit. By this analysis it will help to eliminate all the unnecessary motion, fatigue, delay or breakdown for maintenance planning. Art. 6.8.1 to Art. 6.8.5 shows the performance study of all the components and subcomponents for one month.

6.8.1 TMS of component 1

Here Time Motion study of component 1 i.e. printing machine has been conducted. Output in terms of number of impressions has been shown graphically by bar diagram on daily basis for one month as shown in Figure 6.6. This figure has been generated from the study of time-motion on the basis of one hour for a day. For the lack of space time-motion diagram on hourly basis is given for a single day i.e. 1st day of the month in Figure 6.7.

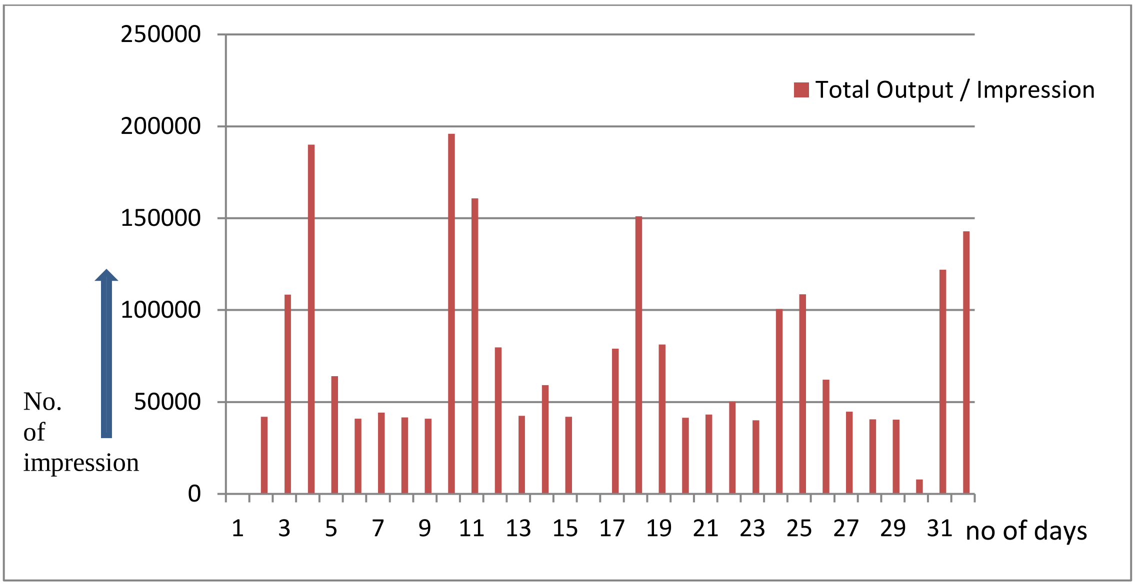


Figure 6.6: TMS diagram of Component 1 on daily basis for one month

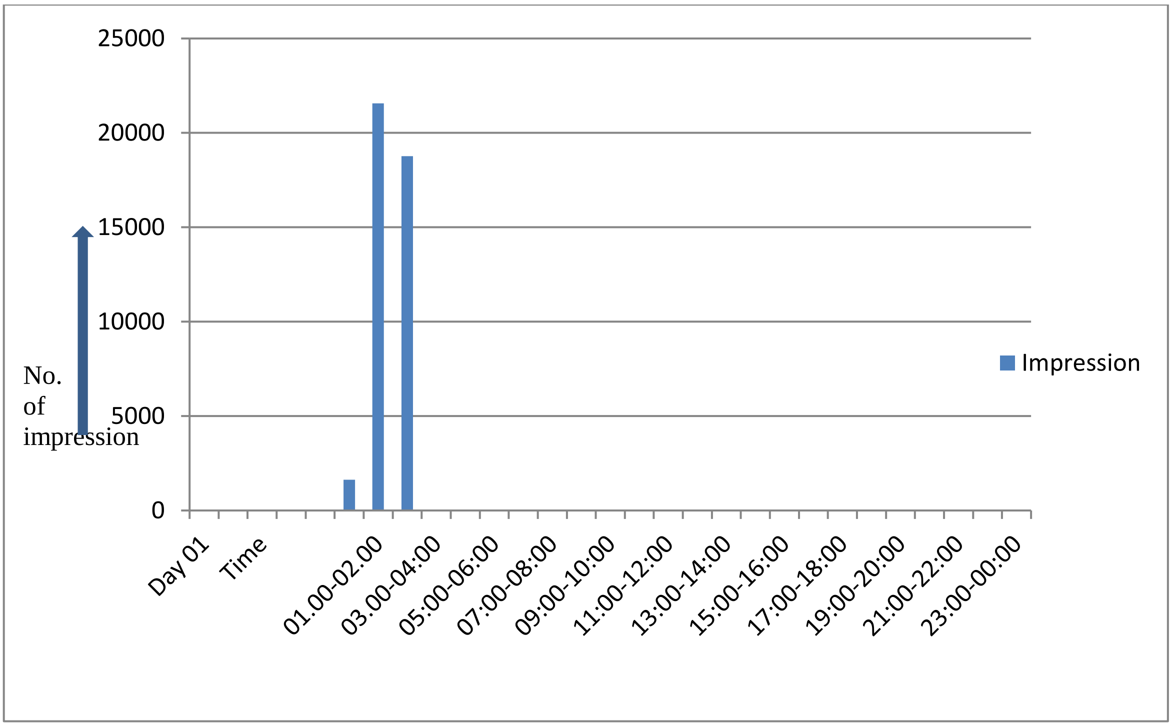


Figure 6.7: TMS diagram for hourly basis for 1st day of the month of component 1

6.8.2 TMS of Component 2

Figure 6.8 shows the time-motion study of component 2 graphically by bar diagram on daily basis for one month and Figure 6.9 shows the time-motion diagram on hourly basis is given for a single day i.e. 1st day of the month.

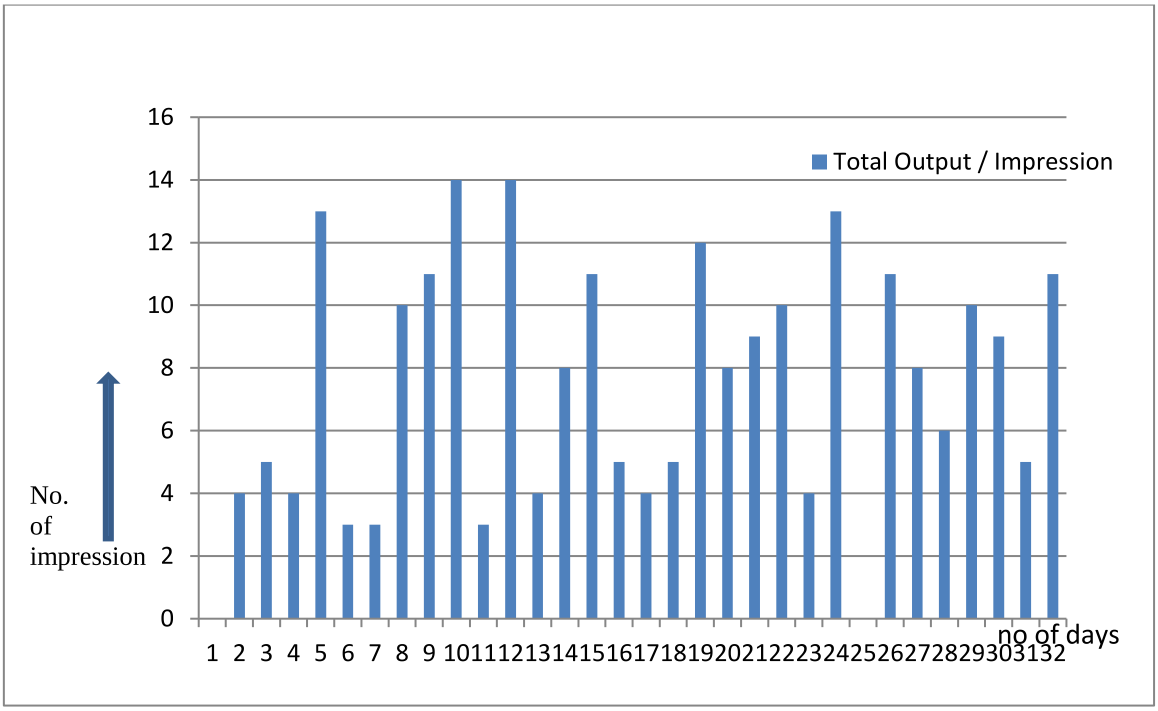


Figure 6.8: TMS diagram of Component 2 on daily basis for one month

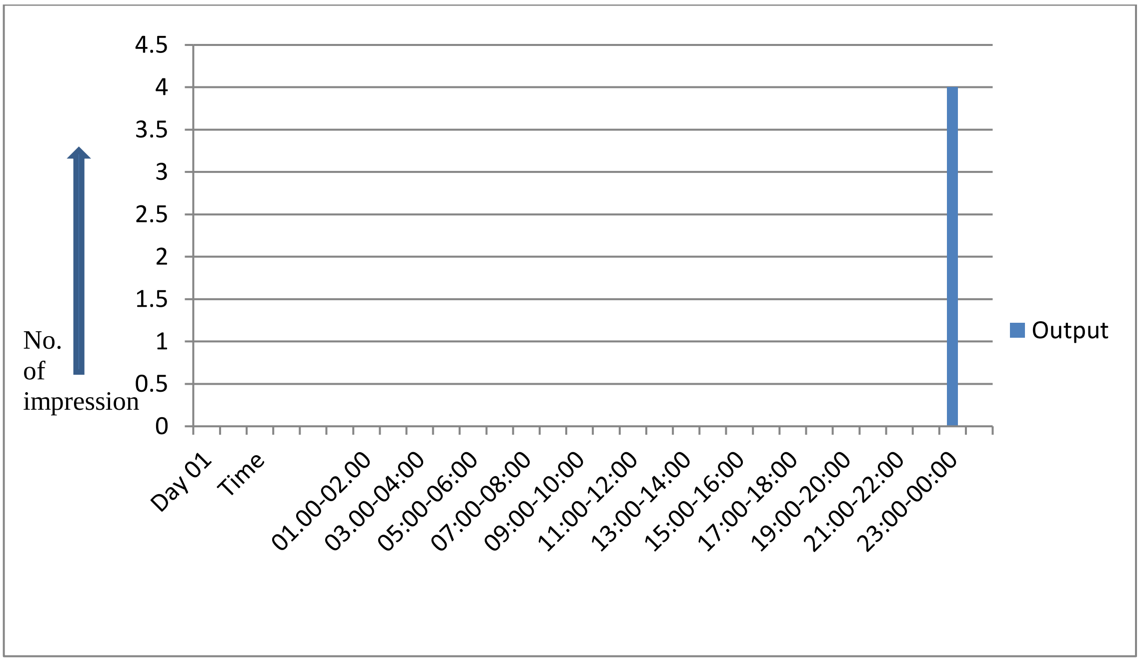


Figure 6.9: TMS diagram for hourly basis for 1st day of the month of component 2

6.8.3 TMS of Component 3

Figure 6.10 shows the time-motion study of component 3 graphically by bar diagram on daily basis for one month and Figure 6.11 shows the time-motion diagram on hourly basis is given for a single day i.e. 1st day of the month.

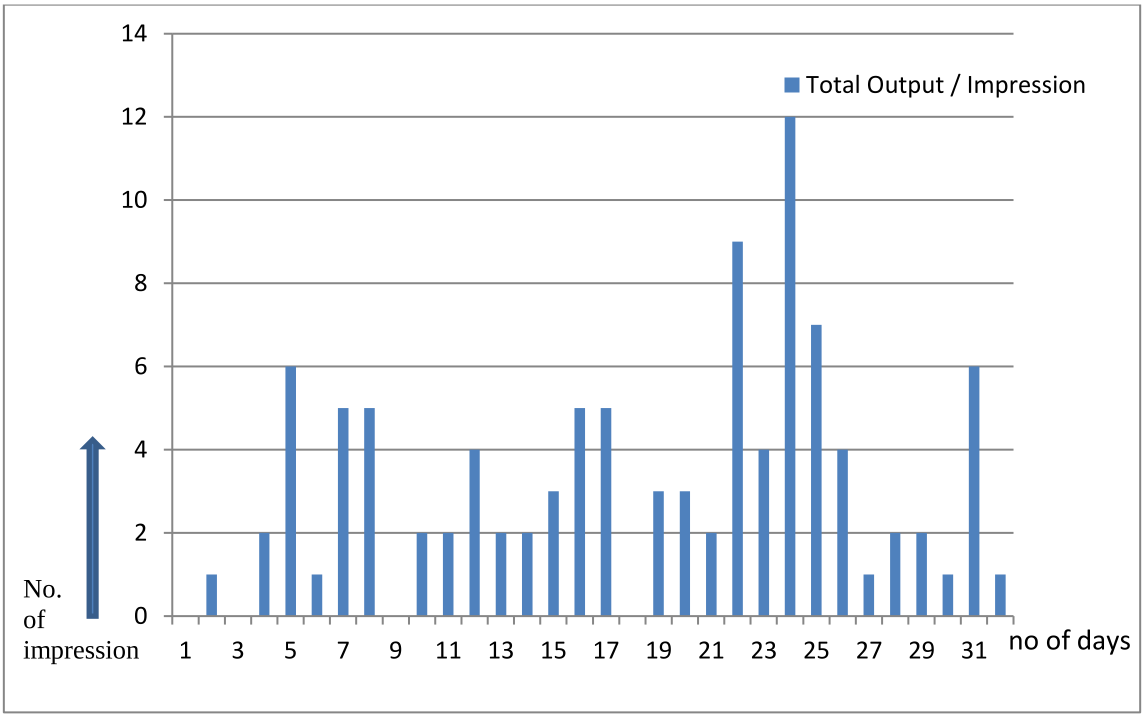


Figure 6.10: TMS diagram of Component 3 on daily basis for one month

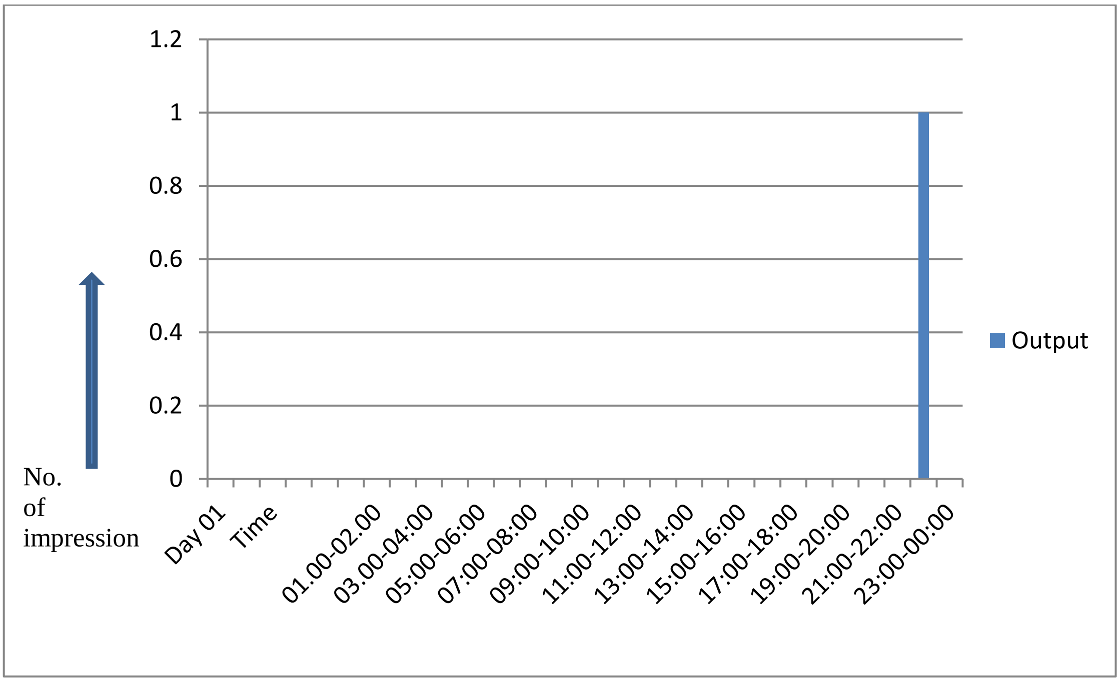


Figure 6.11: TMS diagram for hourly basis for 1st day of the month of component 3

6.8.4 TMS of Sub-component 1

Figure 6.12 shows the time-motion study of sub-component 1 graphically by bar diagram on daily basis for one month and Figure 6.13 shows the time-motion diagram on hourly basis is given for a single day i.e. 1st day of the month.

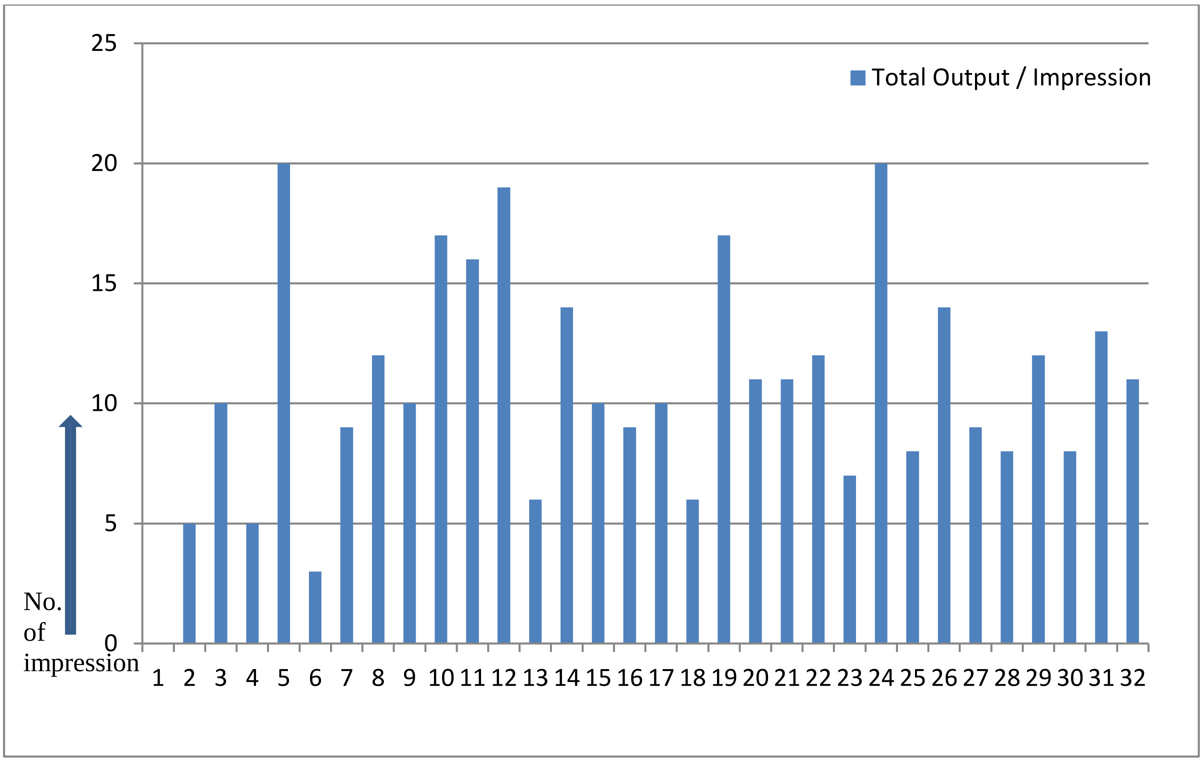


Figure 6.12: TMS diagram of Sub-component 1 on daily basis for one month

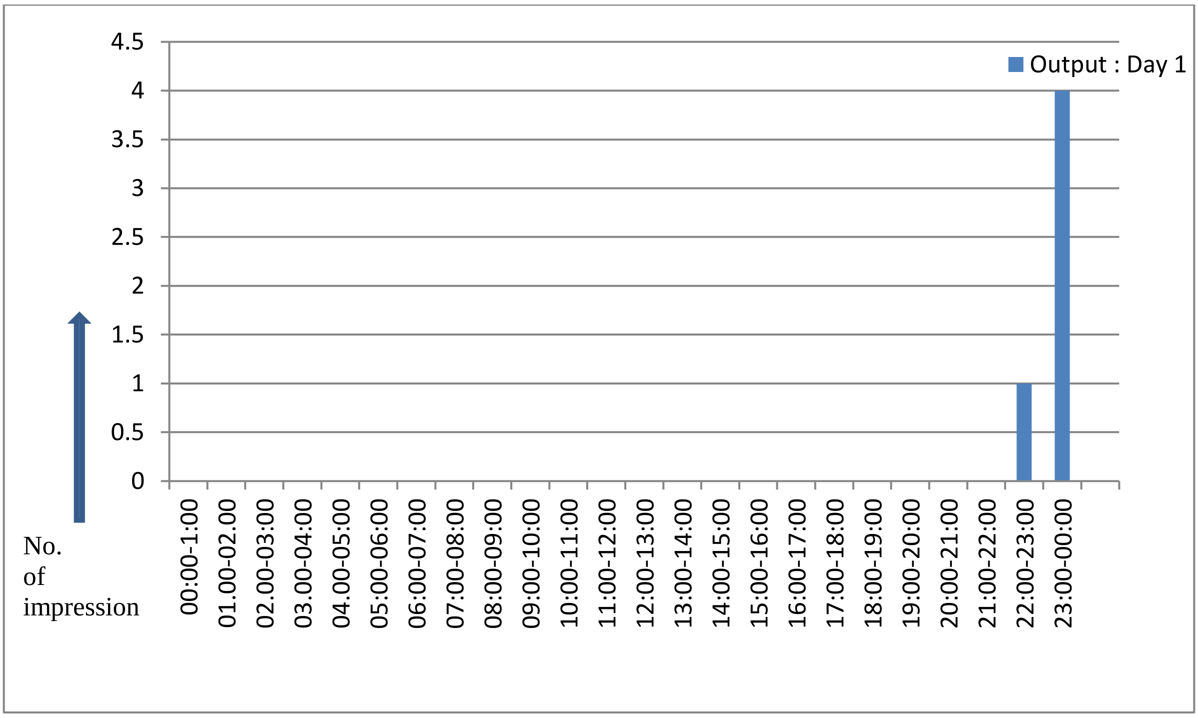


Figure 6.13: TMS diagram for hourly basis for 1st day of the month of sub-component 1

6.8.5 TMS of Sub-component 2

Figure 6.14 shows the time-motion study of component 2 graphically by bar diagram on daily basis for one month and Figure 6.15 shows the time-motion diagram on hourly basis is given for a single day i.e. 1st day of the month.

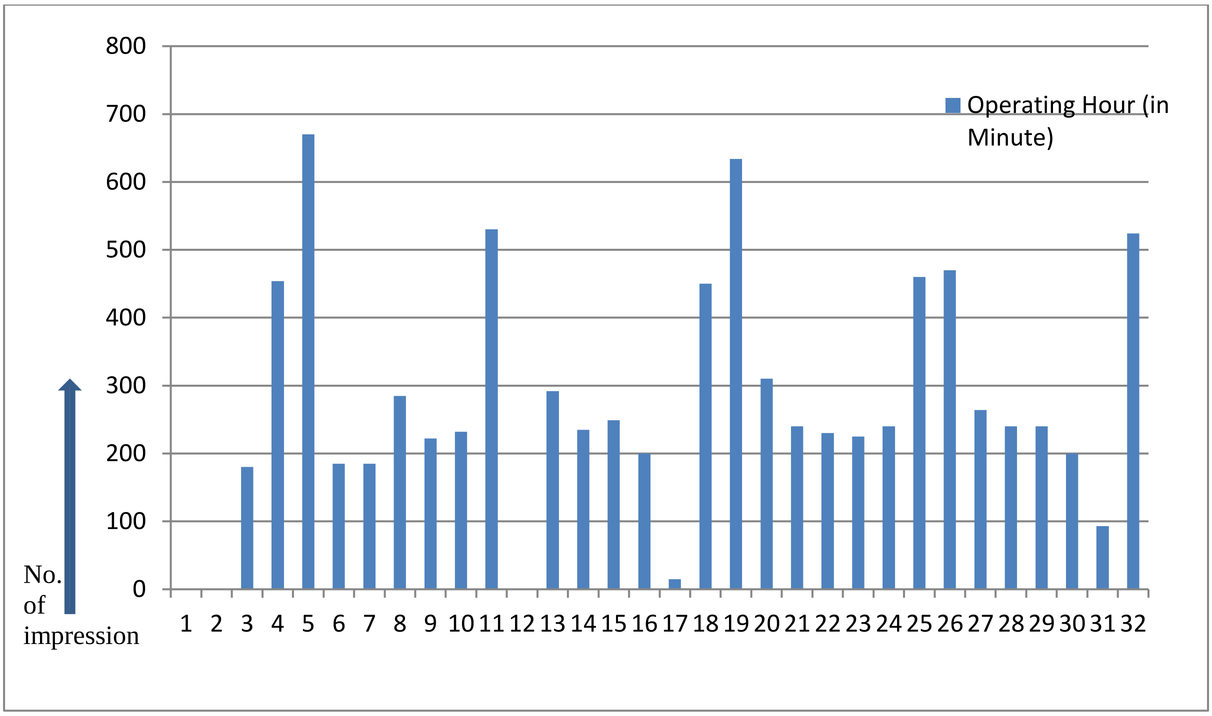


Figure 6.14: TMS diagram of Sub-component 2 on daily basis for one month

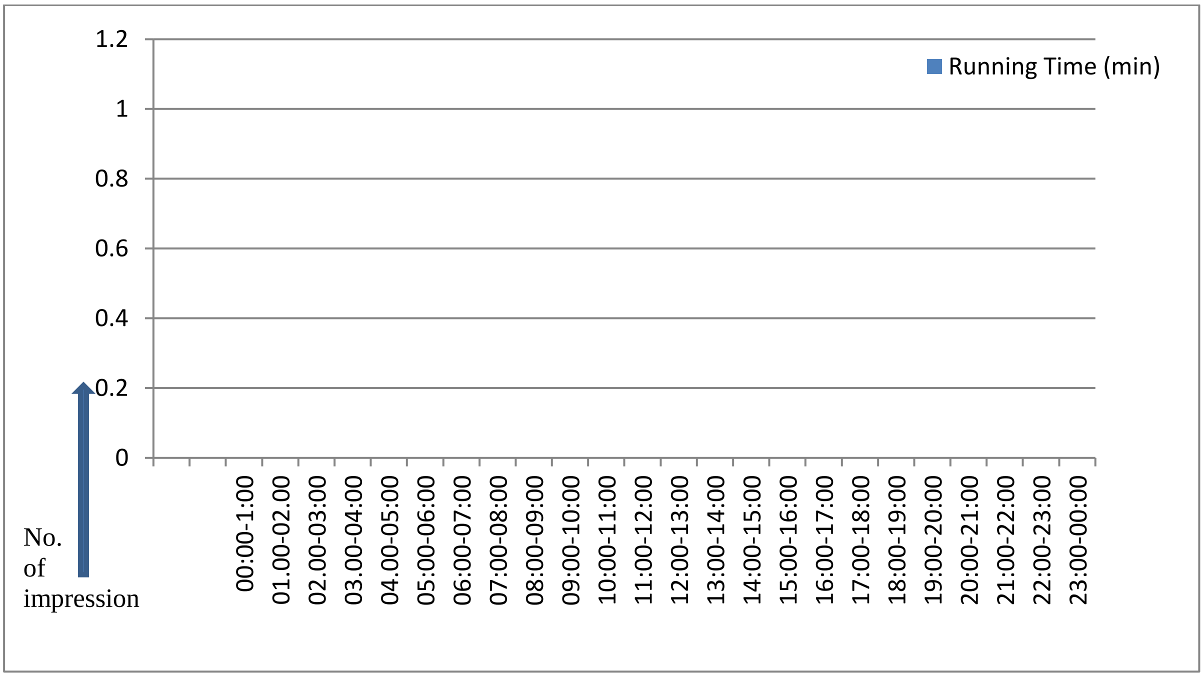


Figure 6.15 : TMS diagram for hourly basis for 1st day of the month of sub-component 2

6.9 Maintainability

In this section the need of maintainability is discussed as it is becoming increasingly important because of the high operating costs of engineering systems for the reduction of maintenance cost and time on the basis of failure analysis, reliability & availability. On the other hand, reliability is a design characteristic that leads to the durability of the system and gives the overview of future maintenance planning. The maintainability of the printing machine is estimated. The table 6.7 shows that the maintainability of the printing machine is 0.29939 on the basis of Weibull analysis (Equation 3.4) respectively.

Table 6.7: Maintainability of Component 1 (printing machine)

No. of days	92
Operating hr	14886
mean operating hr (t)	161.804
Shape (β)	1.83997
Scale (Ƞ)	283.73
Maintainability for Weibull distribution [M(t)]:	0.29939

6.10 Maintenance Planning

The strategy for maintenance planning should be adopted to lower the risk to meet the acceptable criterion, to reduce the probability of failure, to reduce the failure number and AD value, increase the reliability, availability & OEE.

Table 6.8: Risk reduction results

Component	Initial risk	Target probability of failure	Risk reduction in rupees	Modified reliability
Printing machine (C1)	444858.3281	0.22381	180000	0.77619

From the Table 6.8 shows that the risk (in rupees) had decreased to Rs. 180000 (which is the safe limit of acceptable risk criteria) from Rs. 444858.3281 and its corresponding probability of failure also decreased from 0.55313 to 0.22381. Therefore the modified probability of failure for component 1 is 0.22381. As a result reliability will also increase from 44.687% to 77.619%. This will happen when maintenance interval will change approximately from 161.8 minute to 65.4 minute. This has been calculated by considering the modified probability of failure of 0.22381 so that the component 1 i.e. the main printing machine achieves the target probability of failure.

Component	Calculated maintenance interval
Printing machine (C1)	65.4 minute

This is an approach towards risk based maintenance and reliability availability & maintainability strategies to improve overall efficiency of a printing press. Due to lack of time, data is collected only for three month. If data is collected for a prolonged time (one year or above) the result will more precise and accurate.

Chapter 7

CONCLUDING REMARKS

7.1 Discussion

The above observation provides a deep understanding of the fact that how Reliability, Availability and Maintainability (RAM) analysis is influenced by Risk Based Maintenance (RBM) methodology (for Risk Index) and Total Productive Maintenance (TPM) strategy (for Overall Equipment Effectiveness). This can be applied in order to get the reliability and effectiveness of the Printing Press. A maintenance planning is suggested on the basis of the calculation of risk index (R.I.) and overall equipment effectiveness (O.E.E.) Maintenance can be defined in terms of time interval, so that the component can be maintained before breakdown. This study suggests not only the needs of maintenance action of the equipment but also the failure probability and reliability of the machine in terms of ageing. This technique is a great example of a preventive maintenance which amalgamates the principle of proactive maintenance.

In this study R.I. & O.E.E. are calculated before implementation of TPM. It is suggested that R.I. & O.E.E should again be calculated after full phased implementation of TPM in the plant. The results of various analyse in this study determines the suggestions or corrective actions that should be taken into account to minimize the failure probability. It estimates the ranking of high risk component which determines the particular component that should be under maintenance action and the possible maintenance procedures should be applied.

7.2 Conclusion

The present study is based on the implementation of reliability, availability and maintainability of the printing press namely Ganashakti Printers Pvt. Ltd. The collection of the data is the most vital prediction to carry out such analysis. The initial stage of the present study has been involved with the collection of well-defined data regarding the background and the maintenance of printing press. It has been observed that worker inefficiency, degradation of component due to ageing, dirt & debris are the main factors of the failure of printing press components.

The reliability prediction of the printing press components has become fruitful to focus the components having more failure frequency and this must be taken care of. The time motion study and availability pattern of each component describe the performance of the printing press components.

Here the maintenance program has been presented based on the reduction of the risk factor. This approach ensures that reliability of components are increased after implementation of maintenance planning suggested. This will contribute to the availability of the plant as well as its safe operation. In the present approach, only the maintenance interval is considered. This effects the probability of failure directly and the consequences of the risk indirectly.

The present study helps to identify the critical components and subcomponents based on Risk factor and OEE factor. It has been observed that the component1 i.e. the main printing machine is found to have unacceptable initial risk. Reducing the risk of this component a result in overall reduction of the risk of the press.

Therefore detail and continuous study is required for analysing the effects and risk assessment and recommended preventive maintenance for the printing press components and subcomponents on reliability aspects.

It can be concluded that by adapting RAM analysis or technique it can be easily analysed as to when and which machine is to be checked and replaced by the help of cause & effect diagram, Pareto analysis and fault tree analysis. Also this technique is the great example of preventive maintenance which combines the principle of proactive maintenance. The results obtained are quite satisfactory. However there might be a scope of improvement in this work in relation to the time period for which data are collected. The extended period can provide a long term solution. But the study undoubtedly confirms that the RAM analysis works precisely well in a printing press. The findings of the study may be given as a suggestion to the press and positive results may be confirmed after adapting the aforesaid model in the production procedure of the press.

7.3 Scope of future work

The present work and case study can be extended meaningfully for further study in the following areas:-

1. Due to lack of time, data is collected for only three month and result is based upon this. If this period is extended to one year then the result will be more accurate. This can provide a long term solution.

2. In this study only pre-press section & printing section is considered due to lack of time. The post-press section should be considered that will give the desired result for whole printing plant.

3. Development of detailed maintenance plan to reduce risk consideration of data collection for long time span.

4. Detail study of the effects of proposed maintenance intervals on the overall risk of the printing press.

5. Detail study of the effects of the proposed maintenance plan on the availability of the printing press.

6. Further analysis is also required after implementation of total production maintenance (TPM) in the plant. This may help to improve the overall effectiveness of the plant.

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