RELIABILITY ANALYSIS : A REVIEW

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Abstract—Reliability is a very important issue in today's competitive environment. Reliability assessments are necessary for modern engineering systems, such as industrial and energy systems, transportation, offshore structures, bridges, and pipelines, to ensure successful operation over the course of their service life. Deterioration of processes requires studying reliability variation over time, availability, and maintainability. In the present study, a review of different reliability measures is done through many research articles for specific time horizons from different journals for the effective performance of the products. Research in reliability is growing rapidly, covering all disciplines using different tools and techniques. The objective of this article is to analyze all aspects of reliability, which is done by analyzing 72 shortlisted articles from various reputed journals.

***Keywords*— Reliability, Availability, Maintainability.**

1. INTRODUCTION

Modern society demands automation to meet growing demands, but systems and devices operate under various environmental conditions. Failures impact systems like power plants, airlines, and satellite communication, requiring reliability analysis and engineering uncertainty. Reliability engineering covers both qualitative and quantitative aspects, aiming for reliable system design to achieve reliability targets. Reliability technology is crucial to modern industrial growth, focusing on the proper functioning of components and systems to maximize resource efficiency. It has applications in aerospace, defense, electric power generation, transportation, and healthcare. Reliability evaluation ensures the reliability of engineering products, starting in the conceptual design phase. Reliability is an aspect of engineering uncertainty, ensuring the quality and productivity of end products.

1.1 HISTORY

The proverb "Necessity is the mother of invention" also applies to reliability. Due to the demands of modern technology utilised in World War II, reliability and quality control have become increasingly important. The complexity and automation of the military equipment used in the conflict led to serious maintenance and repair issues. Reliability measuring quantitative methodologies have been developed and introduced. The study of reliability and life-testing issues piqued the interest of working engineers and mathematicians.

Germans introduced the reliability idea during World War II to improve rocket dependability. The American Department of Defence established an ad hoc committee, which became the Advisory Group on Reliability of Electronic Equipment (AGREE) [1]. The US held its first national reliability symposium in 1954, and the USAF published the first military specification in 1957 [61]. The first master's degree in system reliability was awarded in 1962. Reference [14] provides a thorough history of the field.

1.2 DEFINITION AND SCOPE OF RELIABILITY

Reliability as a concept predates the existence of man. In its most basic sense, reliability refers to the likelihood that a breakdown won't happen within a specific time frame. Increased system performance under predetermined operating conditions is reliability's primary goal. Reliability is often described as the science of anticipating, analyzing, avoiding, and minimizing breakdowns throughout time.

Definitions	Author
Reliability of a unit (product) is the probability that the unit performs its intended function adequately for a given period of time under the stated operating conditions or environment	Balagurusamy, E., (2010)
The probability that an item will perform its assigned mission satisfactorily for the stated time period when used according to the specified conditions	Dhillon, B. S., (2006)
Reliability is the probability of a device performing its purpose adequately for the period intended under the given operating conditions	Srinath, L. S., (2008)
Reliability is defined as the probability that an item, for example, production or utility asset and work processes, will continue to do what the user needs it to do without failure under specified conditions for a specified period of time.	Mobley, et al., (2008)

The reliability definition emphasizes the following four factors:

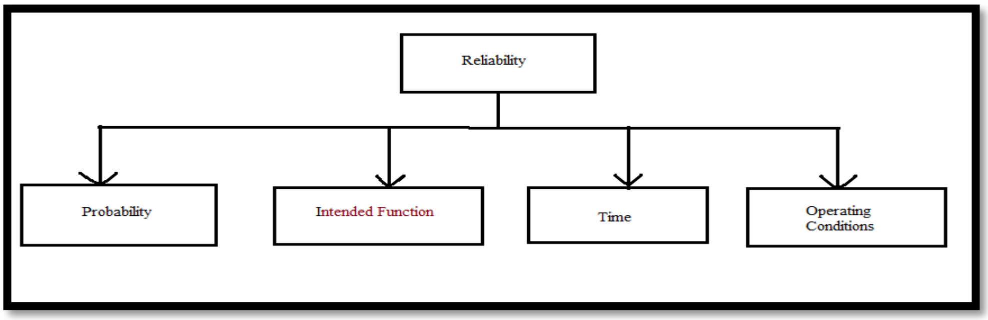

Fig 1. Reliability definition

Depending on the specific circumstances, reliability may be assessed in a variety of ways, such as:
1. MTTF, or mean time to failure
2. The frequency of failures per unit of time (failure rate)
3. The survival probability, or likelihood that the thing won't break in a time interval between 0 to t (survival probability)
4. The likelihood that the thing will work at time t (be available at time t)

The scope of reliability is very vast, and it is one of the most crucial factors taken into consideration [19],[53].

- The system's operational state or working environment
- The requirement for system and human safety
- The degree of uncertainty surrounding the operation's success and the system improvement in performance
- Demand for a smooth, cost-effective, and continuous operating system
- A system failure compels individuals to question the system's reliability and continued use
- An increase in the working personnel's self-assurance, especially in dangerous areas for safety reasons

1.2 Different Failure Causes and Modes

A system's functions may typically be broken down into smaller ones. In the hierarchy, failure modes at one level frequently result from failure modes at the level below it. In order to give traceability to the critical system reactions as the functional structure is developed, it is crucial to connect failure modes at lower levels to the primary top-level responses.

Failure cause, as defined by IEC 50 (191), is "the circumstances during design, manufacture, or use that have led to a failure." To prevent failures or the recurrence of failures, it is essential to know the source of the failure. According to the life cycle of a functional block, failure reasons can be categorized. This is shown in Fig. 2, where the various failure causes are characterized as:

1. Design failure: Failure due to poor design of a functional block.
2. Weakness failure: Failure due to a weakness in the functional block itself when subjected to loads that are within the claimed capabilities of the functional block. **(**A weakness may be induced or ingrained)
3. Manufacturing failure: A failure brought on by a manufacturing process that does not comply with the design of a functional block or to predetermined manufacturing procedures.
4. Ageing failure: A failure whose likelihood of occurring rises over time as a result of mechanisms built into the functional block.
5. Misuse failure: A failure brought on by applying stresses during usage that are greater than the functional block's stated tolerances.
6. Mishandling failure: Failure due to improper or careless handling of the functional block.

The numerous failure mechanisms in Fig. 2 are not always isolated from one another. For instance, it is clear that "weakness" failures and "design" and "manufacturing" failures are related. Failure mechanisms (as in IEC 50(191)) are physical, chemical, or other processes leading to failures, such as wear, corrosion, hardening, pitting, and oxidation. However, this level of description is not enough to evaluate possible remedies, as wear can result from incorrect material specification, misuse, or poor maintenance. These root causes are essential for determining remedial actions.

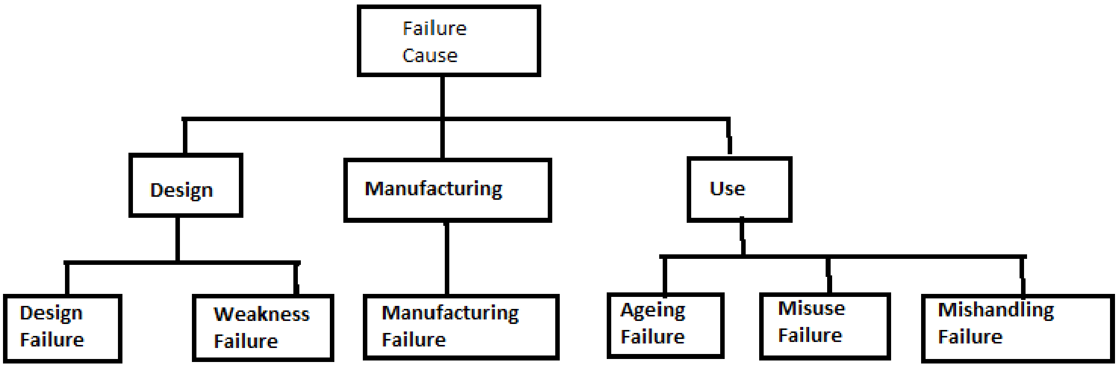

Fig.2 Failure Cause Classification

2. Components of System Reliability

2.1 Reliability

In its most basic form, reliability refers to the possibility that a failure won't happen within a specific time frame.

MTTF: In reliability analysis, The average amount of time an item lasts before failing is known as MTTF. It is the average lifespan of the object.

MTTR: Mean time to repair (MTTR) represents the average time required to repair a failed component or device.

MTBM: The typical interval between maintenance procedures for an asset or component. Both corrective and preventative maintenance procedures may be used in these tasks.

MTBF: "Mean time between failures" or "MTBF" is a term used to indicate the space of time between failures. This is the mathematical total of the mean time to failure (MTTF) and mean time to repair (MTTR), or the average time it takes for a device to break down and deteriorate .

2.2 Maintainability

Maintenance is crucial for ensuring an item's availability and performance under specified conditions. It involves planned and unplanned actions to maintain a system under acceptable operating conditions. Optimal maintenance policies aim to provide reliability, safety, and low costs. Research in reliability engineering focuses on studying various maintenance policies to improve system reliability, prevent failures, and reduce costs.

2.2.1 Major Categories of Maintenance

The major categories of maintenance are:

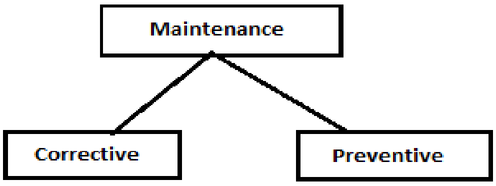

Fig. 3 Categories of maintenance

Corrective Maintenance:

Corrective Maintenance (CM) is the immediate repair of failures to return a system to operation mode, including emergency interruptions. It is an essential component of maintenance activity and involves remedial action to restore equipment to its working state. The five elements of CM are illustrated in Figure 3.

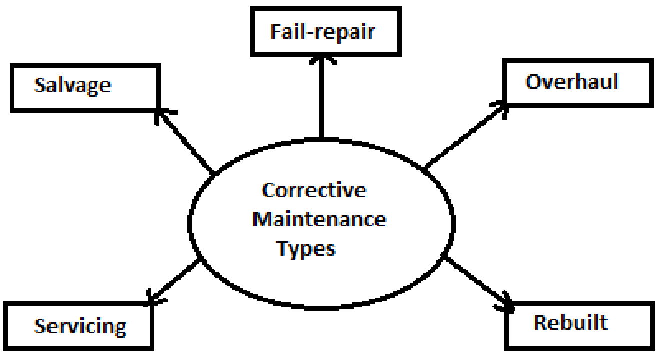

Fig 3. Elements of Corrective Maintenance

The five steps involved in corrective maintenance are shown in figure 4

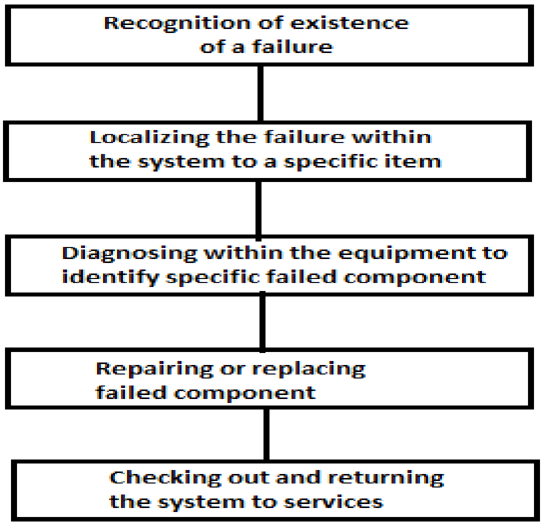

Fig 4. Flow chart of corrective maintenance

Preventive Maintenance:

Preventive Maintenance (PM) is periodic maintenance to increase system reliability by removing wear, corrosion, fatigue, and related issues. Preventive Maintenance is divided into three parts.

- **Scheduled Maintenance**

  Preventive maintenance that is performed in line with a set timeline or a set number of units.
- **Predetermined Maintenance**

  Preventive maintenance is done without first conducting a condition analysis and in accordance with predetermined time or usage intervals.
- **Condition Based Maintenance**

  Preventive maintenance includes monitoring performance and parameter values and taking appropriate action. The scheduling of performance and parameter monitoring can be done constantly or on demand.

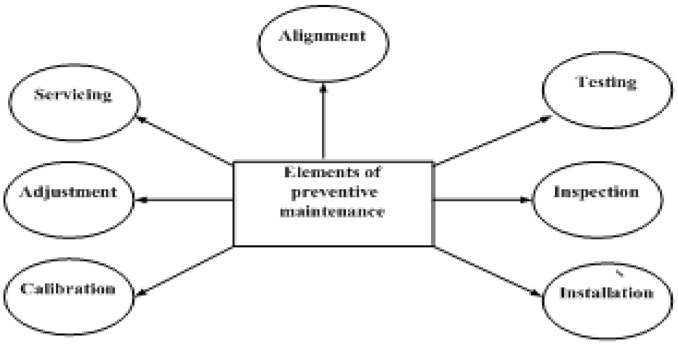

Fig. 5 Element of Preventive Maintenance

Figure 6 explains certain steps, in order to develop a preventive maintenance

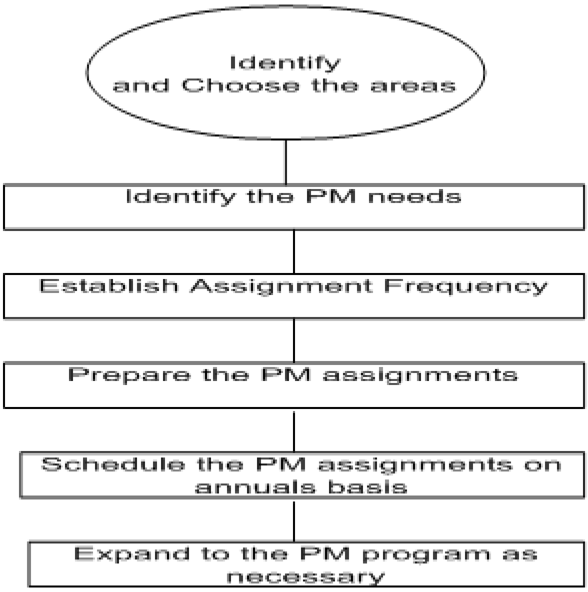

Fig. 6 Flow Chart of Preventive Maintenance Programme

2.2.2 Predictive Maintenance and Operator Maintenance

The importance of highlighting two extra maintenance types are

Operator Maintenance

A qualified user or operator performs maintenance .

Predictive Maintenance

Predictive maintenance is basically the task that is carried out before the occurrence of a failure, and hence, failure can be prevented. Conditions are searched in predictive maintenance that lead to the failure of an item.

2.2.3 Proactive Maintenance

Predictive and preventative maintenance are completely different from proactive maintenance. It is founded on conceptual risk evaluations. Control over maintenance resources is one of proactive maintenance's key attributes.

The following categories of maintenance can also be made based on the degree to which an item's working condition is improved by maintenance:

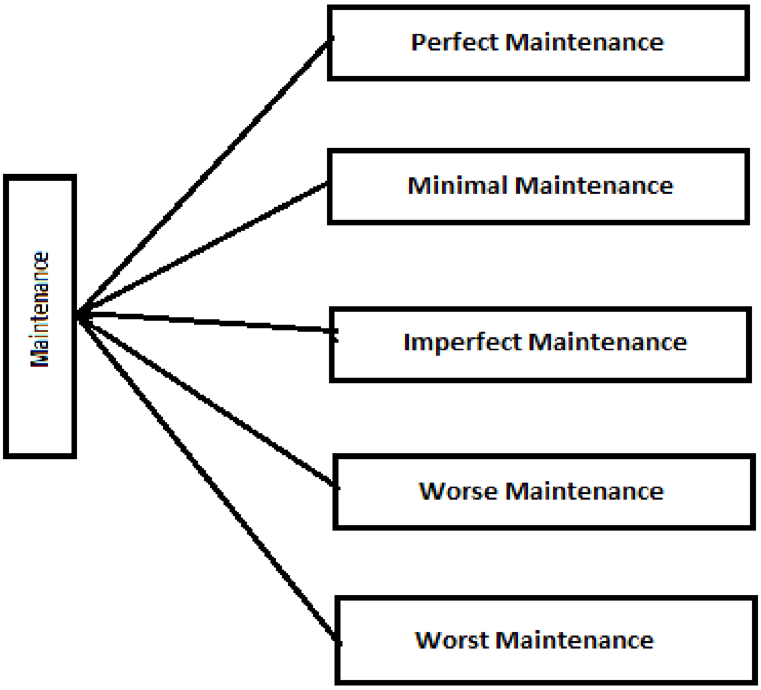

Fig. 7 Classification according to degree

- Perfect Maintenance: Maintenance procedures that make a system operate "as good as new." In most cases, ideal maintenance involves replacing a failing system with a new one.
- Minimal Maintenance: Maintenance procedures that return a system to its previous failure rate.
- Imperfect Maintenance: Maintenance procedures that age a system rather than making it "as good as new" . It is a broad repair that includes the two extremes of minimal and perfect maintenance.
- Worse Maintenance: Maintenance procedures that unintentionally increase the system's age or failure rate without causing the system to malfunction.
- Worst Maintenance: Maintenance procedures that unintentionally cause a system to malfunction or break down. It is caused by
  - Failures and hidden problems that go undetected during maintenance.
  - Human mistake, including incorrect adjustments and additional damage caused during maintenance.
  - Replacing damaged parts.

2.3 Availability

In order to evaluate the effectiveness of repairable systems, availability is a crucial indicator that considers a component or system's attributes for both reliability and maintainability.

$$Availability = \frac{uptime}{uptime + downtime}$$

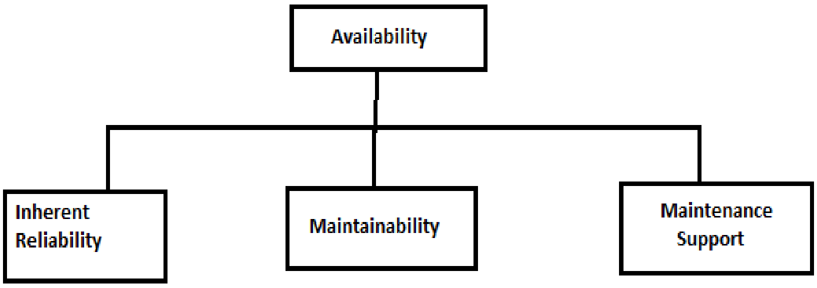

Fig. 8 The availability as a function

Three types of availability can be defined depending on the time:

- Inherent Availability

This is the probability that a system will perform as expected when put to use under specified circumstances in a perfect support environment (with quick access to tools, parts, labour, etc.), without taking into account any preventive maintenance at any given moment. It could be stated as

$$A_i = \frac{MTBF}{MTBF+MTTR},$$

- Achieved Availability

In the definition of inherent availability, We take into consideration MTBF, which does not account for the downtime brought on by preventive maintenance. When we include MTBF in this , then we have the achieved reliability, which is defined as the likelihood that a system would operate effectively when employed in a perfect support environment at any given time. It could be stated as

$$A_a = \frac{MTBM}{MTBM+M}$$

Where M is mean active-maintenance downtime.

- Operational Availability

Probability that a system will perform as expected when put to use under the specified circumstances and in a real-world supply environment at any given time. It could be stated as

$$A_o = \frac{MTBM}{MTBM+MDT}$$

3. Literature Review

The development and application of reliability/availability strategies have seen a surge in popularity over the last few decades in a variety of industrial fields related to maintenance engineering and management. Pioneering researchers have covered the reliability of several process industries using various methods.

Kimura et al. (1995) have addressed the approach to predicting software reliability based on models of software reliability growth provided by an NHPP (non homogeneous Poisson process). Different reliability prediction measures have been found . Using an arena simulation for a single random occurrence simulation and a double spreadsheet, **Kang et al. (2005)** explained how one model describes the system's dependability, time to overhaul, and working accessibility, while the other model describes the support lifecycle cost and is static in nature. A generic system with repairable components that fail randomly and independently was studied by **Kiureghian et al. (2007)** to determine its steady state availability, mean rate of failure, average downtime, and lower bound dependability. For production systems with complicated topologies, **Todinov (2007)** suggested an effective discrete event simulation model and algorithm based on failure losses. Using copula approaches, **Pandey et al. (2008)** evaluated several subsystem reliability measures. For two different types of repair between nearby states and systems, the Gumbel-Houggard family of copula has been utilised to evaluate MTTF, steady-state probability, availability, and cost analysis. **EL-Damcese (2009)** discussed the reliability equivalences of a series-parallel system and explained how a redundancy method can be used to improve the performance of a system. Using the Weibull distribution, **MI-Damcese (2009)** assessed the Series-Parallel system's reliability and MTSF. **Ram and Singh (2009)** have applied the supplementary variable technique, Gumbel-Houggard family copula and Laplace Transformation to the system to obtain state transition probabilities, availability, and cost analysis. **Kumar and Gupta (2010)** estimated the reliability and hazard rate of a Weibull type life testing model and also explained that the proposed model is better than exponential lifetime data. Sah et al. (2010) modelled a real-life system based on a university web server. Different reliability measures have been evaluated by the application of the supplementary variable technique and Laplace transformation. **Mirzahosseinian and Piplani (2011)** used MOD-METRIC, which has given good results in simulation. **EL-Damcese and Temraz (2012)** developed equations for the model to perform reliability and availability analysis of a parallel repairable system using Markov and Supplementary variable methodologies. **Chauhan and Malik (2012)** considered the Weibull failure laws in order to find the reliability and MTSF of a series system of ‘n’ identical components. **Sureria et al. (2012)** used the semi-Markov process and regeneration point technique to stochastically assess the system model, which is a computer system with two identical units, one operating and the other serving as a spare in cold standby. **Krawczyk (2013)** focused on the technological requirements for the reliability of aircraft operation. **Manglik and Ram (2013)** evaluated the reliability measures of a system having four components using supplementary variable techniques and the Laplace Transform**. Nagiya and Ram (2013)** discussed the various characteristics of a satellite communication system using Laplace Transformation and Markov Process Theory. **Chandna and Ram (2014)** have developed a fuzzy time series model in order to forecast the availability of a standby system incorporating waiting time for repair. **Hungund and Patil (2014)** used exponential and Weibull distributions through the chi-square goodness of fit test to fit and test the suitability of the data. **Shekhar et al. (2014)** present a fuzzy analysis of availability using the Markov machine repair model. In order to validate the suggested approach, a numerical example is also considered to examine general repairable systems more accurately. **Andrzejczak (2015)** explained why stochastic modelling is needed for repairable systems. **Kour et al. (2015)** used the concepts of inspection guarantee and replacement in order to improve the reliability of a two-identical unit system. **Chisa et al. (2015)** developed a statistical model in order to evaluate the effect of predictive and preventive maintenance on car performance and also showed that preventive maintenance performed better than predictive maintenance when the parameter values were chosen. **Niwas and Kadyan (2015)** discussed the concept of warranty and the degradation of a maintained system. The supplementary variable technique is used to determine reliability, MTSF, availability, and profit functions. **Niwas et al. (2015)** used the concept of preventive maintenance (PM) beyond warranty and degradation for two reliability models of a single-unit system. Abel’s Lemma and Supplementary Variable Techniques are also adopted to find the behaviour of the system and derive the expressions, respectively. **Bashir et al. (2016)** have analysed a single unit model with controlled and uncontrolled demand factors. The failure time and inspection time of the unit have been discussed. **Chauhan and Malik (2016) analysed the** reliability and MTSF of some series-parallel and parallel-series by considering arbitrary values of the parameters. **Lee and Cha (2016)** considered regular preventive maintenance procedures for a failing, repairable system. **Li (2016)** evaluated the reliability and dependability of a parallel operative redundant system by using the Markov Modelling Technique. **Linden et al. (2016)** looked into the interaction between technical features and interactive functions in the context of system dependability for heavy trucks. Two reliability estimate techniques have been tested to see if they can be applied to both technical and interactive functions. The MTSF and profit analysis of a single-unit system with inspection for the viability of repair after warranty subject to a single repair facility were covered by **Niwas et al. (2016)**. Using the supplemental variable technique, the expressions for reliability, MTSF, system availability, and profit function have been established. The system's steady-state behaviour has been deduced by using Abel's lemma. By using specific values for different characteristics and repair costs, it is also possible to acquire the numerical results for the reliability and profit functions. **Mwanza et al. (2017)** took into account freedom from danger, protection from risk, and injury during the execution of maintenance processes while analysing safety issues in maintenance. **Chauhan and Malik (2017)** obtained the reliability and MTSF of a parallel system by considering Weibull failure laws. By extending the T-X family of distributions, **Celik and Guluksuz (2017)** proposed a new form of exponential distribution and described the hazard function, mean time to failure, and reliability function as well. By applying the supplementary variable technique and integral differential equations, **Shim et al. (2017)** took into account a Non-Markovian redundancy model with interrupted repairs and also produced steady-state availability for the redundancy model. **Cakmakyapan and Ozel (2018)** proposed the Lindley-Rayleigh (LR) distribution, and its flexibility is shown by using life-time data. In order to analyse a non-identical redundant system with two units—one operating and the other in cold standby—**Kumar et al. (2018)** developed a stochastic model. Each component can be in one of two states: either functioning or failing. The switches used to put the standby unit into operation and for repairs and maintenance are perfect. For the purpose of calculating the annual repair rate and required availability for crucial aircraft components, **Kontrec et al. (2018)** took into account a new stochastic model. An approach for analysing the behaviour of an industrial system under the cost-free warranty policy is presented by **Niwas and Garg (2018).** A variety of metrics for a system, including reliability, mean time to system failure, availability, and predicted profit, are obtained using a mathematical model of the system built on the Markov process. An analysis is done on how different parameters affect the way the system performs. **Sharma and Kumar (2018)** considered the workings of a bio-Ethanol production plant, and the model has been solved using the Orthogonal Matrix Method (OMM). With the help of OMM reliability, the MTTF and cost analysis have been calculated. **Khan and Jan (2019)** presented a new generalised distribution labelled as log-logistic weibull geometric (LLoGWG). Hazard, reverse hazard, and quantile functions have been derived for the above distribution. **Migdadi et al. (2019)** took into account the reliability performance of enhanced generic series-parallel systems when analysing the hybrid of hot and cold duplication based on reduction redundancy approaches. **Shinde et al. (2019)** used the Weibull distribution to analyse the system's availability. Under performance-based logistics (PBL), the availability analysis for repair rates of important aviation components such as the aircraft engine, propeller, and avionics has been investigated. The purpose of this article is to increase the capacity of repair facilities while also offering a normative decision-making tool for hiring military logistic services. In order to enhance the soft water treatment and supply plant's operational performance, **Kumar et al. (2020)** obtained the RAM results. **Jain et al. (2020)** consider three identical units, one in standby and two in operative condition. The semi-Markov process and regenerative point were used to find the reliability measures. **Kumar, Pawar, and Malik (2020)** discuss how, in normal weather, a single server is available to perform the repair activity. **Feng and Tong (2020)** presented the main measures to improve the operation and reliability of power systems. **Pant et al. (2020)** studied the availability and cost rate for k-out-of-n:G systems with N failure modes. **Zurek et al. (2020)** tried to discuss the reliability analysis of technical means of transport by taking the example of a selected military unit. **Kumar (2021)** Used the change-point concept to find the reliability of open source software, and to make the model more accurate, multiple change points are considered. **Haung et al. (2021)** study the reliability analysis of structures based on multi-modal optimisation and saddle point approximation in order to improve the accuracy of system reliability prediction. **Ulbrich et al. (2021)** presented a method to find the reliability of an electronic component of a vehicle—a boot lid contactor. With applications to the power grid, **Dehghani, Zamanian, and Shafieezadeh (2021)** presented an approach for adaptive network reliability analysis. **Kundu et al. (2021)** examined the validity of various AI and ML devices and described two critical reliability issues—circuit ageing and endurance—in upcoming neuromorphic hardware platforms. **Chen et al. (2022)** used the Fault Tree Analysis technique to improve the reliability of machine tools. **Ram, Bhandari, and Kumar (2022)** evaluated the different reliability measures of solar road studs by using the Markov process. **Yang et al. (2022)** used reliability-centred maintenance for monitoring the operation condition of manufacturing systems, and to verify this, the author gave an example of a subway flow receiver. **Aia et al. (2022)** studied the high-speed train gear transmission system and considered the improved optimisation allocation strategy as the most appropriate method. **LI et al. (2023)** proposed the Markov probabilistic model, reliability gain, and tolerance gain in wireless networks. **Gholani et al. (2023)** tried to obtain a high level of reliability for a quad copter and compared the results obtained from the firefly algorithm and the genetic algorithm.

4. Research Methodology

The basic research steps for the reliability topic include a literature review of reliability, the formulation of a classification framework, the presentation of the literature review, the gap analysis, and suggestions for more study, all using the classification system to organize the review. The research approach used for this study is shown in Fig. 9.

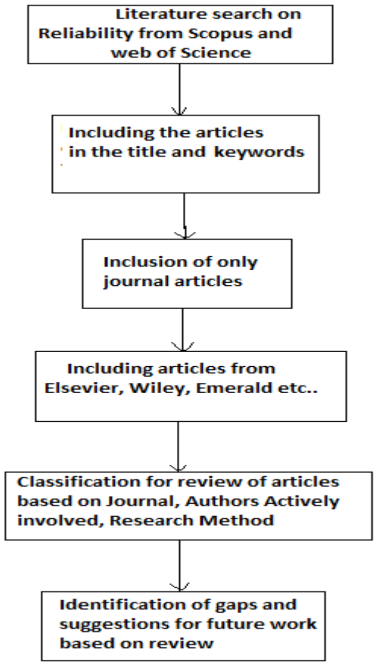

Fig.9 Research Methodology Adopted

5. Classification Framework

After the Review of work done on reliability in the literature, the following classification method was proposed:

1. Journals and Publishers
2. Active Authors

3. Tools and Techniques

6. Analysis of the classification framework

6.1 Distribution of articles based on Journals and Publisher

There are many journals from various streams i.e., from engineering, statistics, information system/ technology etc. that publish the reliability articles. The largest number of articles are published by EKSPLOATACJA I NIEZAWODNOŚĆ - MAINTENANCE AND RELIABILITY, Journal of Reliability and Statistical Studies then followed by International Journal of Quality and Reliability Management, International Journal of Reliability, Quality and Safety Engineering, and many more .

S.No	Journals	Publishers
1	EKSPLOATACJA I NIEZAWODNOŚĆ - MAINTENANCE AND RELIABILITY	Polish Maintenance Society
2	International Journal of Reliability, Quality and Safety Engineering	World Scientific Publishing Co Pvt Ltd
3	Journal of Reliability and Statistical Studies	Ankur Printing Palace
4	IEEE Transactions on Reliability	Institute of Electrical and Electronics Engineers
5	Reliability Engineering & System Safety	Elsevier
6	Quality and Reliability Engineering International	Wiley
7	Microelectronics Reliability	Elsevier
8	Software Testing, Verification and Reliability	Wiley
9	International Journal of Quality & Reliability Management	Emerald Publishing Limited
10	Quality and Reliability Engineering International	Wiley

Table 1 Distribution of articles based on journals

On the basis of research carried in terms of publisher, Elsevier has the highest articles on reliability topic, followed by Wiley, Institute of Electrical and Electronics, Emerald Publishing Ltd., Polish Maintenance Society, World Scientific Pub. At last, Ankur Printing Palace have very few publications. Following figure 10 shows the contribution of publisher .

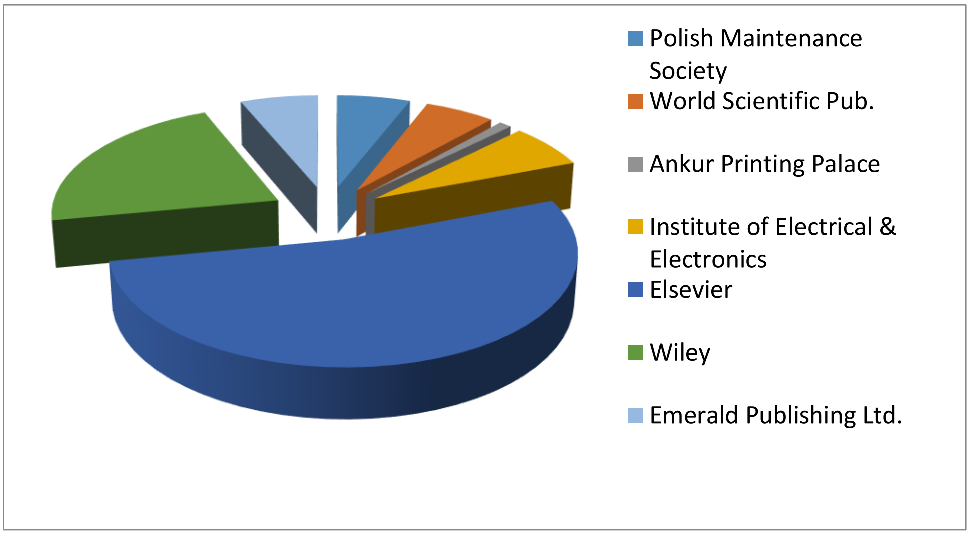

Fig. 10 Distribution of articles based on publishers

6.2 Active Authors

The studies conducted on reliability show that there are some authors who are actively involved in the research related to reliability, availability and maintenance, who participated in the publication of articles. We are considering some authors and co-authors like N. Celik, N. Kontrec, J. Shim, J. Lie, S.C. Malik, S.K. Chauhan, P.K. Kapur, M. A. EL-Damcese, R. Niwas, and M. S. Kadyan, and there are many more who are not listed but have contributed many articles related to reliability.

6.3 Tools and Techniques

Reliability evaluation, a crucial component of reliability engineering, is concerned with ensuring the dependability of engineering products. Numerous reliability evaluation methods and approaches have been created by researchers working in various fields of reliability engineering. Studies conducted on articles based on their reliability show that many different tools and techniques were used. Based on the research, some of the tools and techniques that are widely used in order to evaluate reliability, maintainability, and availability are mentioned below.

- Failure Mode and Effect Analysis (FMEA)
- Network Reduction Method
- Decomposition Method
- Delta-Star Method
- Markov Method
- Supplementary Variables Method
- Laplace Transformation
- Continuous Distributions
- Monte-Carlo Simulation Tools
- The Reliability Block Diagram
- Fault-Tree Analysis
- Minimal Cut and Tie Set Method
- Reliability-Centered Maintenance (RCM)

7. Conclusion

The goal of this study is to learn more sophisticated approaches and methods for researching reliability and its applications in several interdisciplinary fields. It is beneficial to offer a thorough list of journal articles on reliability. This study contributes to a better understanding of the current condition of the discipline's research. Despite the abundance of material on reliability in the journals examined for this review, there may still be room for additional study and application in interdisciplinary fields.

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