

Review Article

A review of reliability techniques for the evaluation of Programmable logic controller

A.F. Obele, D.O. Aikhuele, H.U. Nwosu

Department of Mechanical Engineering, University of Port Harcourt, East-West Road, Port Harcourt, Nigeria

*Correspondence: A.F. Obele (alenjuobele@yahoo.com)

Abstract: PLCs, or programmable logic controllers, are essential parts of contemporary industrial automation systems and are responsible for managing and keeping an eye on a variety of operations. PLC reliability is critical to maintaining industrial systems' continuous and secure operation. A wide range of reliability strategies were used to improve the reliability of Programmable Logic Controllers, and this article methodically looks at them all. The evaluation classified PLC reliability techniques into Root Cause Analysis (RCA), Reliability Centered Maintenance (RCM), Hazard analysis (HA), Reliability block diagram (RBD), Fault tree analysis (FTA), Physics of failure (PoF) and FMEA/FMECA, after thoroughly reviewing the body of literature. The proportion of reviewed papers using either RCA, RCM, FMEA/FMECA, FTA, RBD, RCM, PoF, or Hazard analysis to increase the reliability of PLCs showed that RCA, which makes up 20% of the publications reviewed, has been used the most to increase the reliability of the PLC, followed by HA, RCM, RBD, FTA, and PoF, which account for 17%, 16%, 16%, 13%, 10%, and 8% of the articles reviewed, respectively. The paper discusses new developments and trends in PLC reliability, such as the application of machine learning (ML) and artificial intelligence (AI) to fault detection and predictive maintenance.

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Keywords: Programmable Logic Controllers; Root Cause Analysis; Reliability Centered Maintenance; Physics of failure; Fault Tree Analysis; Hazard Analysis; Failure Modes and Effects Analysis (FMEA); Failure Mode, Effects and Criticality Analysis (FMECA); Reliability Block Diagrams

1. Introduction

The foundation of contemporary industrial automation systems is programmable logic controllers, or PLCs, which orchestrate intricate processes and guarantee the smooth operation of a wide range of manufacturing and control applications. PLC reliability is critical as companies depend more and more on automation for accuracy and efficiency. The robustness, efficiency, and profitability of industrial processes are directly impacted by these controllers' capacity to tolerate failures and disturbances.

With a focus on the various issues that arise in the deployment of PLCs, this paper attempts to thoroughly examine the landscape of reliability strategies used with PLCs. PLCs are vulnerable to a variety of threats due to the increasing need in industrial systems for increased functionality and connectivity. Software bugs, hardware malfunctions, and communication problems can all have serious repercussions, from compromising safety procedures to causing production to stop.

This paper aims to give a thorough analysis of the different reliability tactics and methodologies that have been created to strengthen PLCs against possible malfunctions. Through a comprehensive review of the literature, we hope to provide a unified knowledge of the cutting-edge methods used to improve the reliability of these controllers.

2. Techniques in Reliability

The term "reliability technique" refers to the various instruments used to evaluate the reliability of a system, component, or device. The methods used to assess the reliability of engineering systems include the ones listed below:

2.1. Root Cause Analysis (RCA)

Root cause analysis (RCA) is the primary technique maintenance and reliability engineering specialists employ to tackle issues that affect an organization's capacity to achieve strategic goals. Managers, engineers, supervisors, operators, and technicians use RCA as a methodical process to get rid of persistent issues that have an impact on a company. Not simply for equipment breakdowns, RCA is the ideal method for resolving several issues (Reliability, 2021) [1]. With the advent of the Toyota production system and the lean manufacturing methodology, root cause analysis has gained popularity as a problem-solving technique.

With the active assistance of the Petroleum Safety Authority, Vinnem *et al.* (2010) [2] presented a study conducted as part of ongoing research aiming at identifying significant risk-influencing elements for major hazard risk in the Norwegian petroleum business. Marquez *et al.* (2010) [3] demonstrated how time-to-failure distributions may be modelled and reliability analysis of complicated systems can be carried out in a straightforward, unified manner using new Bayesian network (BN) methods. Mello *et al.* (2010) [4] provided an example of a qualification failure. A method for enhancing the identification of the root cause of electrical component failures through the application of a system-related failure anamnesis approach was presented by Jacob (2015) [5]. Reliability provisioning is pursued by Alirezaeyan *et al.* (2015) [6], using the first replication strategy (*i.e.*, concurrent transmission).

A technique for evaluating the reliability of systems when failure events can be explained by time-variant parallel and/or series systems was introduced by Savage & Kap Son (2011) [7]. Yao *et al.* (2011) [8] introduced a self-consistent approach that takes the influence of skin effect into account when designing a two-level Cu interconnect structure for high-frequency dependability. A succinct analysis of the failure modes and mechanisms of electronic assemblies under various loading scenarios was conducted by Mattila & Paulasto-Kröckel (2011) [9]. Larcher & Padovani (2010) [10] went into great detail about the technological alternatives that were suggested to get over the scaling limits of Flash memory devices. These proposals included the addition of a charge-trapping layer and high- κ materials in both the bottom and top dielectric stacks.

Tiwari & Roy (2013) [11] used the Cox proportional hazard model to assess the failure rate and its causes. Chan *et al.* (2013) [12] used a semiconductor device with fault latency to verify the efficacy of the Environmental Stress Screening (ESS) approach. Roesch (2012) [13] examined the relationship between conventional quality indicators and early life failures that are not detectable or predictable by the customarily smaller sample sizes used in life testing. To assist in efficiently allocating resources, Chang *et al.* (2012) [14] provided an extensive overview of industry and scholarly research on the dependability and failure mechanisms of light-emitting diode (LED) technologies to LED inventors and end-product makers. The programming procedures, failure mechanisms, and anti-fuse structures of anti-fuse Field Programmable Gate Arrays (FPGAs) were covered by Patil *et al.* (2013) [15].

The core reason for a high resistance issue caused by changes in the fabrication process and mismatched design criteria was examined by Naoe *et al.* (2012) [16]. The objective of Chen *et al.* (2013) [17] was to evaluate the growing reaction of the Ni₃Sn₄ intermetallic compound (IMC) during the bonding process and its dependence on the Cu/Ni/SnAg micro-joints' thermal-cycling reliability under accelerated thermal cycling (ATC) loading in an advanced 3D chip stacking package. To determine why the defects occurred at such a later stage of development, Silva *et al.* (2017) [18] presented a root cause

analysis of 1070 defects discovered in four space software projects during Independent Software Verification and Validation (ISVV). They did this by using an improved Orthogonal Defect Classification (ODC) taxonomy and looking at the defect types, triggers, and impacts.

Transient thermal testing was used and improved upon by Elger *et al.* (2016) [19] to track the LED modules' structural integrity during accelerated stress testing. Based on plant experiences, Kim *et al.* (2017) [20] presented a workable framework to statistically quantify the levels of socio-psychological PSFs using data on human error. Thermal impedance analysis was employed by Magnien *et al.* (2017) [21] to track solder joint fatigue during an applied supply switching test (SST). A better definition of a prime implicant was created by Tyrväinen (2016) [22] to meet the requirements of dynamic reliability analysis.

Analogue circuit simulation was used by Boostandoost *et al.* (2017) [23] to support the PFI (Physical Fault Isolation) to shed light on the failure processes and the device's operation when it was malfunctioning. An improved Weibull-Corrosion Covariate model was presented by Okaro & Tao (2016) [24] to assess the reliability of a system under operational stress. The thermo-mechanical stress that axial lead fuses, which are utilized in power electronics, undergo was examined by Bahman *et al.* (2017) [25]. To supplement the current approaches, Mohammadnazar *et al.* (2019) [26] introduced a proactive, qualitative approach that is independent of fault data.

A novel approach to reliability analysis of coherent systems susceptible to random external shocks and internal breakdowns was presented by Huang *et al.* (2019) [27]. The excellent reliability of the power semiconductor was demonstrated in Stiasny *et al.* (2018) [28] summary of test results from accelerated testing, quality monitoring results over many years, reliability data from evaluated field failure rates, and analysis of devices that were in service for 15 years under well-known load. Low *et al.* (2018) [29] focused on reliability problems resulting from IC design flaws. They presented a case study of a 28 nm input/output (I/O) circuit reliability failure and demonstrated a full workflow, beginning with failure analysis (FA) and Final Test (FT) to identify the root cause of the problem and concluding with design retrofit to fix it.

The Markov/CCMT search engine platform framework for dynamic system reliability modelling and analysis was introduced by Yang *et al.* (2019) [30]. To measure the risk and performance of big, complex systems with dynamic behaviours, Penttinen *et al.* (2019) [31] created an Open Modelling approach for the Availability and Reliability of Systems (OpenMARS). Peng *et al.* (2018) [32], presented a novel model for recurrent data of repairable systems with misuse-induced failures and normal-operation failures, based on a non-homogeneous Poisson process (NHPP) and a trend renewal process.

The implementation of the factor framework supporting the quantification module of the Commission Error Search and Assessment (CESA-Q) technique was given by Podofilini *et al.* (2021) [33]. Ding *et al.* (2021) [34] presented a novel method based on fault tree analysis (FTA), fuzzy Bayesian network (FBN), and failure mode and effect analysis (FMEA) for the reliability assessment of the residual heat removal system (RHRS) for the Hualong Pressurized Reactor 1000 (HPR1000). 345 passenger car recalls that were submitted to the National Highway Traffic Safety Administration were examined by Chi *et al.* (2020) [35].

The extended Phoenix approach was employed by Chen *et al.* (2021) [36] for qualitative analysis. To determine the primary cause, Sun *et al.* (2021) [37] examined the failure mechanism. A thorough investigation using the evidentiary network was conducted by Mi *et al.* (2022) [38] for the reliability analysis of complex systems with mixed uncertainty and common cause failures. In Xu *et al.* (2022) [39], metallographic observation, cupping tests, and tensile testing were used to assess the quality and dependability of the flash butt welding (FBW) junction of a 50JW800 silicon steel strip.

Zhang *et al.* (2022) [40] describe how an underground gas storage firm employed a bimetallic composite pipe that failed as a gas transmission conduit. A load-sharing man-machine system with multiple man-machine units (MMUs) that is vulnerable to random shocks, human error, and machine degradation was examined by Che *et al.* (2022) [41]. A unique approach to handling missing data was presented by Morais *et al.* (2022) [42] and involved the use of intervals that included the lowest and highest potential probability values. A broad hierarchical ensemble-learning framework (ELF) with three phases and two-layer models was presented by Zhou *et al.* (2022) [43] for reliability analysis.

To enable a methodical examination of the satellite communication system's dependability, Chen *et al.* (2023) [44] first modelled it using a Markov Bayesian Network in combination with a non-working reserve system. In a complicated procedure involving ongoing learning, Arias Velásquez (2020) [45] presented a unique paradigm for autonomous root-cause defect investigation. A data-refined, physics-guided architecture for fault root cause tracing (FRCT) was proposed by Xu *et al.*, (2023) [46]. Arias Velásquez & Mejía Lara (2020) [47] suggested a clever neural network classifier for transformer defects that was tweaked using an intelligent genetic algorithm.

It helps manufacturing businesses with their ongoing efforts to reduce production costs, productivity, quality, and maintenance (Bhamu & Sangwan, 2014) [48]. There has been some research on the use of RCA in reliability analysis, such as the presentation by Ito *et al.* (2022) [49] of the obstacles and facilitators found in recent research relating to the various phases of root cause analysis. RCA prioritization of production disturbances was studied by Soares *et al.* (2022) [50]. The writers used a series of interviews to research the current state of manufacturing companies.

In addition, a series of seminars involving experts in the field, including practitioners and academics, identified the stakeholders and factors affected by production interruptions. Reid & Smyth-Renshaw (2012) [51] looked into the mechanics of root cause analysis (RCA) and the viability of the "5W + 1H" (what, why, when, where, who, how) technique, which is employed by many managers to comprehend a problem and identify its fundamental cause. Because of the differences brought on by asking "why," the 5W + 1H methodology is insufficient for determining the core cause. Although catastrophic failures were frequently the result of misinterpreting the "why" question, the study shows that some exceptional RCA was achieved by changing the approach of the 5W+1H methodology.

As a result, the article identifies a new domain that may be included in projects that follow the conventional RCA and Six Sigma methodologies. Abdelrahman & Keikhosrokiani (2020) [52] studied historical data for two assembly line machines to detect anomalies and their root causes; future work can focus on predicting when these anomalies will occur rather than just focusing on when they occurred, which could lead to faster and more effective decision-making. Singh & Jagannath (2016) [53] demonstrate how to use Root Cause Analysis to reduce product defects within a Gloves Manufacturing Unit.

Mousavinia *et al.* (2020) [54] investigated the cause of a severe failure in bolts in an oil and gas production plant's low-pressure (LP) section of a gas turbine. Bolt failure was reported alongside massive failures of turbine blades in the second stage of the turbine's hot section. To demonstrate the advantages of this methodology for improving engineering design and plant operation reliability, Nascimento *et al.* (2013) [55] used two actual accidental situations from a multinational air separation company. They used a systematic and organized RCA methodology. To forecast unpredictable behaviour, Mohammadnazar *et al.* (2019) [26] suggested a strategy that depends on finding inconsistencies between development practices and development circumstances.

To enhance the effectiveness of root cause analysis, Ma *et al.* (2021) [56] created a big data-driven root cause analysis system. To determine the root reasons for failure and suggest workable alternatives, Viveros *et al.* (2014) [57] suggested a novel fusion of RCA

with the notion of imaginative problem-solving. For enterprises to successfully perform RCA in a networked and data-intensive Quality 4.0 environment, Barsalou (2023) [58] compiled information about Quality 4.0 and guided on what upgrades to implement. Using a strategy for a literature review, Papageorgiou *et al.* (2022) [59] reported the most recent developments in Root Cause Analysis (RCA) for Zero-Defect Manufacturing (ZDM).

2.2. Reliability Centered Maintenance (RCM)

Reliability Centered Maintenance (RCM) is a broad strategy for managing complex systems' maintenance and reliability requirements (Deepak & Jagathy, 2015) [60]. With the main objective of guaranteeing that the equipment is capable of running as necessary and generating the anticipated outcome, the reliability-centred maintenance methodology is a very effective and useful methodology for carrying out plans of preventive and predictive maintenance chores (Sifonte & Reyes-Picknell, 2017) [61].

The two most common types of maintenance are corrective and preventive. Corrective maintenance is any maintenance performed after a system has failed. Preventive maintenance is performed while the system is in operation, with the primary goal of avoiding unexpected failures (Luo *et al.*, 2015) [62]. Its purpose is to reduce the likelihood of failure or to improve equipment performance. Preventive maintenance is also classified as predictive, Total Productive Maintenance (TPM), or Reliability-Centered Maintenance (RCM) (Niu *et al.*, 2010) [63].

A unique condition-based maintenance system was introduced by Niu *et al.* (2010) [63]. It optimizes maintenance costs through the use of reliability-centred maintenance mechanisms and uses a data fusion technique to improve prognostics, health assessment, and condition monitoring. A modelling methodology based on reliability analysis was presented by Macchi *et al.* (2012) [64] to aid the maintenance management of railway facilities. A comparison analysis is presented by Das Chagas Moura *et al.* (2011) [65] to assess the efficacy of the Support Vector Machine (SVM) in predicting the reliability and time-to-failure of manufactured components using time series data.

The fatigue reliability of a fixed jacket offshore wind turbine at a sea depth of 70 meters, intended for a northern North Sea location, is examined by Dong *et al.* (2012) [66]. Using monitored strain data from crawl tests, Okasha *et al.* (2012) [67] devised and demonstrated a method for upgrading the lifetime reliability of ageing bridges. Without the need for simulations, Guan *et al.* (2012) [68] introduced an effective analytical Bayesian strategy for upgrading system response and dependability. A probabilistic computational framework for the Pareto optimization of preventative maintenance applications to bridges in a highway transportation network was described by Bocchini & Frangopol (2011) [69].

Martorell *et al.* (2010) [70] introduced an expansion of RAM+C models that incorporates the impact of both people and material resources. A reliability-centered predictive maintenance plan was presented by Jiang *et al.* (2015) [71] for an Inertial Navigation System (INS) with multiple redundant components and a complex structure. Rhayma *et al.* (2013) [72] introduced a novel approach to examining the behaviour of railroad tracks. A reliability study based on a general data-driven framework was proposed by Lin *et al.* (2015) [73] to demonstrate how degradation data can be modelled and analyzed to flexibly determine reliability during the formulation of preventive maintenance strategies. The study used both classical and Bayesian semi-parametric degradation approaches.

For the life-cycle maintenance of structural systems, Barone & Frangopol (2014) [74] examined probabilistic techniques based on the yearly reliability index, annual risk, and lifetime distributions. Song *et al.* (2014) [75] investigated the reliability of multi-component systems with different shock sets that are susceptible to dependent competing risks of wear degradation and random shocks. Reliability analysis and vulnerability

analysis are two methods for gathering information needed to comprehend and enhance essential infrastructures, and Johansson *et al.* (2013) [76] compared and contrasted them. A Bayesian model updating method (BMUA) was introduced by Peng *et al.* (2013) [77] for the life cycle dependability assessment of innovative products.

Chamseddine *et al.* (2014) [78] tackled the issue of optimal dependability in systems with excessive actuators. With reference to several classes of distribution system assets, Dashti & Yousefi (2013) [79] concentrated on asset management in electrical distribution systems. To guarantee prompt operation and maintenance (O&M) services, Si *et al.* (2022) [80] proposed an agile maintenance framework in which technician assignment and maintenance schedules were coordinated. Si *et al.* (2022) [80] creatively presented a workable and efficient method for real-time precision reliability prediction of the worm drive system backed by digital twin. To evaluate the dependability of a multi-parameter monitoring system for Intensive Care Units (ICUs), de Araujo *et al.* (2022) [81] created a modular and parametric model.

A strategy based on Bayesian networks (BNs) was put forth by Fan *et al.* (2022) [82] to maximize the gas supply reliability in networks of natural gas pipelines. For time-dependent reliability analysis, Mathpati *et al.* (2023) [83] presented a novel model-agnostic data-driven reliability analysis paradigm. By utilizing the ideas of the well-known multifactorial evolutionary algorithm, Chowdury *et al.* (2023) [84] utilized the ideas of the well-known multifactorial evolutionary algorithm (MFEA) to present a novel method for evolutionary multi-task optimization in the reliability redundancy allocation problem. Li *et al.*'s (2023) [85] evaluation of the high-speed rail (HSR) ballastless track structure's service dependability took into account the influence of the irregularities' wavelength distribution characteristics.

The suitability of the Reliability Centered Maintenance (RCM) approach for evaluating reliability concerns and maintenance requirements for unmanned cargo ships was investigated by Eriksen *et al.* (2021) [86]. Bressi *et al.* (2021) [87] presented an approach designed to assist in the development of the best preventive maintenance plans that may preserve a railroad track bed's acceptable quality level while lowering the life cycle maintenance expenditures' current value. A modeling and simulation methodology was proposed by Li *et al.* (2021) [88] to assess a cloud data center's service reliability from the three perspectives of connectivity, performance, and service.

Ma *et al.* (2020) [89] looked into the methodologies for maintenance optimization and reliability analysis of a two-unit warm standby cooling system. A human reliability analysis method tailored for railway applications was suggested by Catelani *et al.* (2021) [90] to create a time-dependent model of the chance of human mistake during a work shift. Chen, *et al.* (2021) [91] developed a performance margin-based reliability study for an airplane lock mechanism that takes wear and multi-source uncertainties into account, based on the principles of reliability science. A novel reliability model for systems with clusters of dependent component degradation paths was presented by Yousefi *et al.* (2020) [92], and the gamma process was selected for the stochastic degradation modelling.

A framework for analyzing product reliability using data from online consumer evaluations was presented by Pan *et al.* (2020) [93]. Colombo *et al.* (2020) [94] used machine learning techniques to address the downhole safety valve reliability estimation challenge. A two-stage shock model with a self-healing mechanism was presented by Zhao *et al.* (2018) [95] as an expansion of the cumulative shock and delta-shock models. The SMP (Semi-Markov Process) was used by Li *et al.* (2018) [96] to address the issue that non-exponential distributions govern the lifetime of the components in dynamic systems. An innovative approach for integrated maintenance decision-making based on operational conditions data, theoretical reliability estimation, and condition monitoring data of belt conveyor systems was presented by Liu *et al.* (2019) [97].

A triple-level network opportunistic maintenance (NOM) approach for multi-location production lines was presented by Si *et al.* (2019) [98]. The goal of RCM is to

develop a maintenance strategy that reduces total operating costs while increasing system reliability (David *et al.*, 2017) [99]. Diego *et al.* (2016) [100] developed a multi-objective genetic algorithm-based approach for reliability-centred maintenance programs in electric power distribution systems. Ahmad (2017) [101] investigated a framework for the application of reliability-centred maintenance in the lead oxide production system. Tamer *et al.* (2016) [102] presented the implementation of failure mode and effect criticality analysis (FMECA) and fishbone techniques in reliability-centred maintenance planning.

Fuentes-Huerta *et al.* (2021) [103] assessed the reliability of the RCM methodology using a combination of Fuzzy Numbers and the Maximum Entropy Method. Using failure modes and effect analysis (FMEA) as a tool, Okwuobi *et al.* (2018) [104] provide information on the steps and procedures to identify critical components of the Individual Section-forming Machine (ISM) using the reliability data of the equipment's functional components to develop an ideal and effective maintenance program. The traditional and simplified RCM models were used to create a recommended model that will be effective and efficient, focusing on the system's primary operations to prevent or eliminate unnecessary maintenance actions and find beneficial maintenance chores (Afefy *et al.*, 2019) [105].

2.3. *Physics of failure (PoF)*

The physics of failure is a reliability design technique that uses knowledge and comprehension of the mechanisms and processes that cause failure to forecast reliability and enhance product performance. The life of a product under its intended use conditions is estimated using the physics-of-failure (PoF) approach to reliability, which makes use of an understanding of the mechanisms and processes that cause product degradation (Hendricks *et al.*, 2015) [106]. To increase system reliability, researchers have proposed various PoF techniques. For example, Tamsamani *et al.* (2017) [107] proposed a methodology that will enhance reliability estimation and enable a gradual transition from a prediction handbook-based approach to a PoF-based reliability assessment.

Kostandyan & Sørensen (2012) [108] developed the physics of failure approach for electrical components owing to temperature loading. To forecast the reliability life of electronic devices, Jiao *et al.* (2019) [109] created a simulation scheme that combines heat analysis, vibration analysis, and reliability simulation. Using this scheme, they then analyzed a control circuit board in an Inertial Navigation System (INS). To evaluate complicated electronic systems, Sun *et al.* (2021) [110] presented a novel method that combines the copula Bayesian network and the physics of failure (PoF) method. An overview of the planning and implementation of power converter reliability testing, together with a look at in-field health management, was provided by Martino *et al.* (2023) [111].

A methodology for estimating the dependability of offshore wind turbine blades with high availability and cost-effectiveness was presented by Zhang *et al.* (2023) [112] by integrating the direct probability integral method (DPIM) with transfer learning (TL). Based on the Physics-of-Failure (PoF) theory, Mulenga *et al.* (2022) [113] presented a methodology for forecasting the emergence of a fracture in corroded structures. Gu *et al.* (2023) [114] introduced a new framework for creep-fatigue reliability assessment of high-temperature components, in which the engineering damage mechanics technique is used to integrate the physics of failure and monitoring data into the natural degradation process.

Jiang *et al.* (2021) [115] developed the subset active subspace method (SASM), a unique supervised dimension-reduction strategy, for estimating the high-dimensional reliability problem with an exceptional failure event. Based on uncertainty theory, Chen *et al.* (2021) [91] investigated the epistemic uncertainties in the reliability assessment of the system with trigger effect. Mi *et al.* (2020) [116] introduced a methodical approach to reliability assessment that utilizes the notion of survival signature to evaluate the

dependability of intricate systems that consist of several component kinds. A thermal modeling-driven method for characterizing the effects of hot solder dipping on electronic components is described in detail by Stoyanov *et al.* (2013) [117].

For qualification and lifetime evaluation of electronic devices, such as super capacitors, Temsamani *et al.* (2018) [118] used the Physics-of-Failure (PoF) methodology. Using experiments and Finite Element (FE) simulations, Yongle *et al.* (2020) [119] examined the physics of die-attach joint failure in Insulated Gate Bipolar Transistors (IGBTs) based on the evolution of micro-defects in materials under accelerated ageing. Fu *et al.* (2018) [120] suggested a method based on PoF models to forecast the lifespan of a System-in-Package (SiP). The power module, DC-link capacitors, and control circuitry are the three main subsystems that are the focus of Squiller *et al.* (2014)'s [121] PoF-based system-level reliability assessment process.

The authors presented examples of ways to increase subsystem reliability based on the evaluation approach, and they also described the primary failure types and processes for each subsystem. Chookah *et al.* (2011) [122] used a mechanistic superposition model as a benchmark to develop a simple empirical PoF model to describe the degradation of X-70 carbon steel structures as a function of physical parameters. Zhu *et al.* (2016) [123] developed a probabilistic Physics of Failure-based framework, for fatigue life prediction of aircraft gas turbine discs operating under uncertainty. Using piezoelectric cells, Kamara *et al.* (2010) [125] examined problems related to the design of a small vibration test apparatus. An integrated application of many numerical analytical techniques and related analysis tools for damage prediction and design optimization in electronics packages and microsystems was reported by Xue *et al.* (2011) [125].

The framework takes into account the overall uncertainties that arise during a structural integrity assessment. Shao *et al.* (2014) [126] discussed the design and analysis method of physics-of-failure-based reliability and introduced the development of physics-of-failure-based reliability technology from the demands of equipment development. Sakurahara *et al.* (2019) [127] initiated a research line that combines renewal process modelling with probabilistic models of underlying mechanisms associated with physical degradation and maintenance. The author's methodology combined Markov modelling with Probabilistic Physics-of-Failure (PPoF) degradation models, while maintenance was handled using a data-driven approach.

2.4. Fault Tree Analysis (FTA)

Fault Tree analysis converts a physical system into a logical diagram, making it one of the industry's most popular methods for calculating reliability and safety. It can also change the configuration of a system to make it less vulnerable and sensitive (Ruijters & Stoelinga, 2015) [128]. Fault trees can also evaluate the impact of proposed design changes or corrective actions (Yong & Ba, 2010) [129]. The top-down deductive analysis is used to determine the causes of an event. A fault tree analysis is made up of "events" and "logic gates," which connect the events to determine the cause of the top unwanted event. The completed fault tree is evaluated in light of the analysis goals.

Zixian *et al.* (2011) [130] evaluated time-independent and dependent components jointly by combining a fault tree with Markov models. Abdul Rahman *et al.* (2013) [131] created a new technique that uses customer-weighted values of component failure frequencies and downtimes to forecast the customer reliability of a distribution power system using the fault tree approach. In addition to developing numerous new measures for fault diagnostics, system failure intensity, system failure count, and configuration control, Vaurio (2010) [132] demonstrated an effective order for computing important measures.

A new technique for analyzing large coherent fault trees was described by Contini & Matuzas (2011) [133]. This technique can be used to an advantage when working memory is insufficient for creating Binary Decision Diagrams (BDD). The application of a Bayesian

network (BN) in accident occurrence probability estimate and updating in light of new information was demonstrated by Khakzad *et al.* (2011) [134]. Chiacchio *et al.* (2013) [135] presented a composition algorithm that addressed the generalization of the hierarchical technique for the reliability evaluation of dynamic fault trees. The formalism known as generalized FT (GFT) was developed by Codetta-Raiteri (2011) [136] by integrating the primitives from three pertinent Fault Tree (FT) extensions: parametric, dynamic, and repairable FT.

The General Dependency Model (GDM), which models the probabilistic dependencies between components using a Bayesian network, was proposed by O'Connor & Mosleh (2016) [137]. Son *et al.* (2016) [138] offered a methodical way to assess the dependability of intricate fault-tolerant systems by streamlining the Markov model using system failure rate and system unavailability rate. Zhai *et al.* (2018) [139] proposed a novel combinatorial approach that enables the efficient reliability analysis of large-scale redundant Phased-mission systems (PMSs) with dynamic demand requirements. This approach involves the construction of a unified aggregated binary decision diagram (ABDD) model that takes into account all mission phases.

To improve wearer comfort and safety, Yu *et al.* (2018) [140] introduced a sequential time-dependent reliability analysis method that takes into account the temporal sequence and correlation of failure processes for the lower extremity exoskeleton under uncertainty. According to Chen *et al.* (2018) [141], failure mechanisms (FMs) can be categorized into three types: combination load-triggered (C-type), operational load-triggered (O-type), and environmental load-triggered (E-type) FMs. Sahu & Palei (2022) [142] used generated sensor data and 28-month logbook records to provide a data-driven method for fault analysis of drag systems utilizing an inference-based Bayesian network (BN). An effective combinatorial approach is presented by Wang *et al.* (2022) [143] for the reliability study of smart home sensor systems (SHSSs) that are susceptible to competition between the propagated sensor failures and the local gateway failure.

The evaluation is divided into several stages: listing minimum cut sets, grading minimum cut sets, calculating probabilities, and so on. FTA is very useful when there is quantitative data on the likelihood of events, but qualitative analysis is also possible (Ruijters & Stoelinga, 2015) [128]. Other risk analysis approaches are less effective than fault trees at detecting flaws. Its visual representation of failure causes makes identifying a single failure that leads to a complete system failure simple. A fault tree is frequently normalized to a given interval, and the probability of an event is determined by the relationship between the event risk function and this interval. The reliability is computed using a gate sequence that takes into account the probabilities of the outputs of a set of Boolean logic operations.

It can also be used to evaluate the effects of recommended remedial actions or design improvements (Yong & Ba, 2010) [129]. Monte Carlo simulation and deterministic algorithms are two important techniques for establishing minimal cut sets for fault trees. Figure 1 illustrates a fundamental fault tree topology. The literature claims that FTA is utilized in the HEMM fault analysis. In the previous five years, several studies utilizing SFT and DFT have been published. From the prior work, it can be shown that FTA is used to make decisions on optimal maintenance intervals, qualitative and quantitative fault analysis, and equipment dependability assessments using both descriptive and numerical data mixed with Boolean algebra (Ali *et al.*, 2014) [144].

FTA was useful in determining Risk Priority Number (RPN), equipment value, and influence on value. It also helped to discover fundamental failure-causing events and construct mathematical models by logically linking the events. To comprehend the consequences of each component or subsystem of a dragline on its reliability and to get insight into an efficient maintenance plan, Tuncay & Demirel (2017) [145] performed a fault tree analysis. The probability distribution that most accurately characterized the data for each dragline subsystem was found. The effect of each component's reliability on a

dragline was then determined by combining the acquired distributions with a fault tree for describing the system.

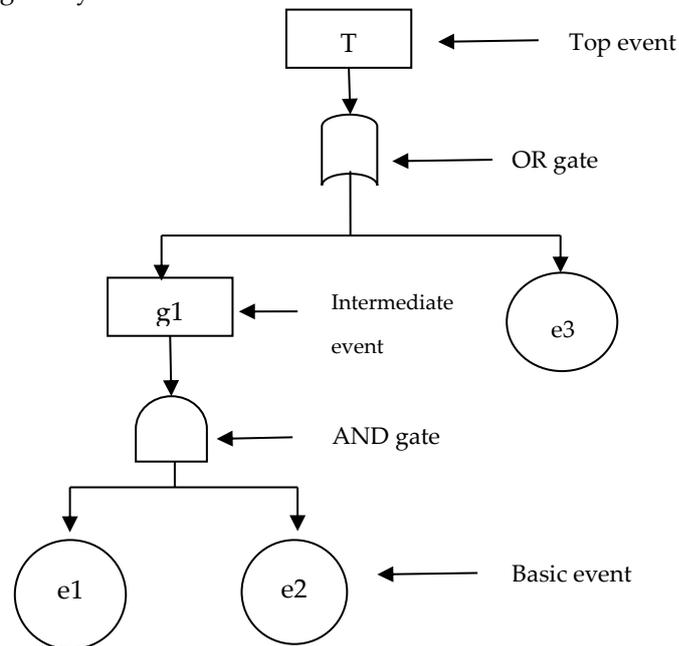


Figure 1. Basic fault tree. Source (Kang et al., 2019) [146].

Most failures are anticipated to be caused by dragging rope within a year, although the motors and generators will have the longest downtime. Probability values were also helpful in determining which components require attention and when. Patil et al. (2019) [147] employed fault tree analysis to identify CNC turning centre faults. The failure tree (FT) diagram and the machine's governing reliability model were both evaluated using Boolean algebra. To pinpoint the essential parts and subsystems of a CNC turning centre, qualitative and quantitative analysis is used.

The findings include an evaluation of the CNC machine's dependability after one year of the warranty period and a count of failures during this time. The failures connected to the mine cage conveyance were examined by Iyomi (2021) [148] using fault tree analysis, which also demonstrated the various failure-causing events' potential branches and the order of criticality for the various connected components. The effectiveness of the mine cage conveyance as a system was affected by failures related to one or more components, so efforts were made to manage the essential components identified in this study by assessing the current maintenance plans and creating more effective techniques.

Based on the impact on production, impact on value, availability standby, and equipment value, Relkar (2021) [149] developed a methodology to identify the company's critical machine. This machine was then thoroughly analyzed using failure mode and effect analysis and fault tree analysis to determine its risk priority number (RPN). The severity rating, chance of occurrence, and probability of detection combine to form the Risk Priority Number (RPN) (Li et al., 2021) [150]. Twenty-seven (27) fundamental events lead to hydraulic failure in the hydraulic system, with oil pollution being the most important basic event, according to a case study that employed a fault tree for a hydraulic system on a heavy-duty machine.

If uncertainties are not resolved, there is a potential that inaccurate results may be obtained since the accuracy of the numerical data utilized in the analysis completely determines the conclusion of quantitative analysis. As a result, many approaches mostly based on fuzzy numbers were suggested to deal with the problem of ambiguous failure data in FTA. Only static systems can have their dependability evaluated using Standard

Fault Trees (SFTs). Many dynamic failure characteristics, including functional dependent events and failure event priority, result from a system's dynamic nature.

SFTs are frequently used for dependability analysis, although they cannot capture dynamic data. Dynamic fault trees (DFTs), state event faults, and stochastic hybrid fault trees are a few ways that SFTs have been extended to help with dynamic dependability analysis. The DFT covers sequence-dependent behaviour, component behaviour that is dependent on function, and event priority, making it one of the most often used dynamic extensions of the SFT (Kabir, 2017; Jiang *et al.*, 2021) [151, 152]. Jiang *et al.* (2021) [152] suggested a technique for configuring a road header's dynamic fault tree.

The fault tree was divided into dynamic and static states using the modular technique; the static state was examined using a binary decision tree, and the dynamic module was evaluated using the logical relationships between faults. For an electric haulage shearer, Wang *et al.* (2012) [153] created a dynamic fault tree employing a binary decision tree and the Markov method in a modular way. According to the analysis, the shearer's defects were primarily caused by improperly installed first shaft bearings, a cage of the first shaft bearing, damaged cutting motors, and poor-quality lubricating oil (Ruijters & Stoelinga, 2015) [128]. Although numerous fault tree extensions have been suggested, each one has several drawbacks.

Many investigations require a sizable amount of manual labour, even when technological tool assistance is available. To make dependability analysis simpler, academics have concentrated on approaches to automate the synthesis of dependability information from system models. Hence, the discipline of "Model-Based Dependability Analysis" (MBDA) has developed (Ruijters & Stoelinga, 2015) [128]. Several methods and tools for automating the creation of dependability analysis, including fault trees, have been created as part of MBDA. The analyses in MBDA can be iterated because they are based on formal models, which helps to produce additional results and new results if the system architecture changes.

This process is quicker and less expensive than manual methods, and because it is more structured, there is less likelihood of providing inaccurate or incomplete results during the study. Moreover, the MBDA approaches provide a higher level of reusability by allowing portions of an existing system model or libraries of previously examined components to be reused (Ruijters & Stoelinga 2015; Yong & Ba 2010) [128, 129]. The Irrelevance Coverage Model (ICM) was expanded by Zhou *et al.* (2022) [154] to Dynamic Fault Trees (DFTs) with Priority-AND (PAND) gates.

Ding *et al.* (2021) [34] developed a novel method based on Failure Mode and Effect Analysis (FMEA), Fault Tree Analysis (FTA), and Fuzzy Bayesian Network (BN) (FBN) approaches for the reliability assessment of the Residual Heat Removal System (RHRS) for Hualong Pressurized Reactor 1000 (HPR1000). The design-phase safety analysis of vehicle guidance systems is taken into account by Ghadhab *et al.* (2019) [155]. An approach for modelling the uncertainty propagation in fault trees was presented by Yilmaz *et al.* (2023) [156]. Bhattacharyya & Cheluyan (2019) [157] offered a technique for improving the cost and dependability of a system represented by a fault tree.

2.5. Hazard analysis

It is common practice to accomplish system safety by methodically examining dangers through the process of "hazard analysis," which is a strategy for detecting potentially dangerous system components (Jung *et al.*, 2020) [158]. The reliability of the system has been the subject of a variety of research projects on hazard analysis, such as the creation of a new Proportional Hazard (PH) model with the degradation trend and environmental component as covariates, which was suggested by Zheng *et al.* (2021) [159]. The degradation trend was initially represented using the Wiener process, after which the temperature and degradation trend were utilized as covariates to create the PH model,

and finally, a closed form of dependability was established using the Taylor approximation.

A reliability-based study for determining essential tool life in machining processes was provided by Patiño & Gilberto (2010) [160]. Al-Dabbagh & Lu (2010) [161] provided an example of how the Dynamic Flowgraph Methodology (DFM) is used to describe Networked Control Systems (NCSs). A multi-component system CBM policy based on the proportional hazards model (PHM) put out by Tian & Liao (2011) [162]. Jin *et al.* (2011) [163] illustrated its application in a Markov model and covered some significant modelling concerns for Safety instrumented system (SIS) reliability performance quantification. Marquez *et al.* (2010) [3] demonstrated how time-to-failure distributions may be modelled and reliability analysis of complicated systems can be carried out in a straightforward, unified manner using new Bayesian network (BN) methods.

A framework outlining a broad approach to Failure Process Modeling (FPM) was introduced by Regattieri *et al.* (2010) [164]. A method for designing or retrofitting interface topologies to reduce cascading failures in urban infrastructure systems was presented by Ouyang & Dueñas-Osorio (2011) [165]. The Recursive Decomposition Algorithm (RDA) is the foundation of a non-simulation-based network reliability analysis method developed by Kim & Kang (2013) [166] for risk assessment of generic networks whose operation is defined by the connections of many initial and terminal node pairs. A methodology for assessing human reliability based on the Bayesian Belief Network (BBN) was published by Martins & Maturana (2013) [167].

This method was then applied to the operation of an oil tanker, with a particular emphasis on the risk of collision accidents. Within the framework of a vulnerability assessment, Zio & Golea (2012) [168] conducted a study of an electrical transmission network system to determine its important components. Nascimento *et al.* (2012) [169] presented a methodical approach to investigating the risks involved in complicated jobs, especially in situations where risk data is scarce. A method to improve the decision-making process for ordering replacement parts when businesses need to guarantee a reliability level constrained by a lead time was presented by Godoy *et al.* (2013) [170]. An integrated probabilistic approach to blackout analysis was proposed by Henneaux *et al.* (2012) [171].

This approach can handle the coupling between events in a cascade failure and the dynamic response of the grid to stochastic starting disturbances. A structural reliability technique was used by Kostandyan & Sørensen (2012) [108] to provide a more thorough explanation of the reliability and to incorporate all pertinent uncertainty. A quick reliability estimation technique was presented by Kang & Kliese, (2014) [172] for node-pair connection analysis in lifeline networks, particularly in cases where there is a statistical correlation between the network's constituent parts. The non-deterministic dynamic analysis and reliability evaluation of structures with constrained but uncertain parameters under stochastic process excitations were presented by Do *et al.* (2014) [173].

Barabadi *et al.* (2014) [174] used a case study to illustrate how to apply the available reliability models with variables in the field of spare part forecasts. An applied approach to calculate the inter-urban transportation systems' connection reliability and vulnerability to network disturbances was made available by Muriel-Villegas *et al.* (2016) [175]. A novel approach to measuring the dependability of complex systems was introduced by Dunn & Wilkinson (2017) [176], utilizing methods from network graph theory. A comprehensive Bayesian modelling framework was presented by Li & Liu (2016) [177] for statistical hazard modelling of latent heterogeneity in lifetime data.

A basic class of bivariate reliability function based on usage rate was introduced and several bivariate reliability characteristics were examined for warranty claims data by Kumar *et al.* (2017) [178]. Using field return data, Altun & Comert (2016) [179] developed an accurate reliability prediction model for complicated electrical products with high volume sales. Yoo *et al.* (2016) [180] built a water supply system reliability evaluation

model that takes seismic hazards and current methods to improve the hydraulic reliability of the design into account. A framework for the best possible maintenance of wood poles exposed to non-stationary hurricane hazards and deterioration was introduced by Salman *et al.* (2017) [181].

The latest developments in the assessment of the fragility of vital transportation infrastructure exposed to various geotechnical and climatic hazards were examined by Argyroudis *et al.*, (2019) [182]. According to Valdez Banda *et al.* (2019) [183], a comprehensive and methodical hazard analysis must be developed from the very beginning of an autonomous vessel's design process. The probability propagation method (PrPm), a newly developed approximation analytical technique, is presented by Tong & Tien (2019) [184] as a means of estimating the dependability of generic complex networks. A logical dependability assessment of ship constructions under various threats across their lifetime was presented by Liu & Frangopol (2018) [185].

Liu *et al.* (2018) [186] suggested a reliability analysis method for modelling and inferring monotonic degradation using a Bayesian model averaging approach. Bensaci *et al.* (2023) [187] looked into the viability of using intricate multi-mobile robotic systems in hazardous and dynamic settings, such as laboratories and industrial plants, where people are present. Zhou *et al.* (2022) [188] introduced a novel approach that employed the hazard rate matrix and Markovian approximation to simulate the deterioration and reliability of multi-function complex systems.

Li *et al.* (2023) [189] provided a system for simulating the stochastic seismic response of real structures using the probability density evolution technique (PDEM). Consecutive-k-out-of-r-from-n subsystems: F balanced system with load sharing was presented by Wu *et al.* (2022) [190], taking into account both linear and circular architectures. A Kriging-based probabilistic framework was proposed by Bi *et al.* (2023) [191] to assess the multi-hazard performance of structures. The framework is applied to a transmission tower-line system (TTLS) that is subjected to combined wind and rain loads, taking into account the directionality and dependency effects of variables related to wind and rain.

A unique system hierarchy-based model that could provide steady bathtub hazard rates (BHRs) and rising hazard rate functions (HRFs) was put forth by Du & Sun (2022) [192]. A unique approach to handling missing data was presented by Morais *et al.* (2022) [42] and involved the use of intervals that included the lowest and highest potential probability values. Modeling tools for precise dynamic reliability evaluations of systems with independent and non-identical discrete phase-type (DPH) distributions for component lifetimes were proposed by Alkaff (2021) [193]. Byun & Song (2021) [194] introduced a generalized framework that uses a junction tree (JT) to create a Bayesian network (BN) for system reliability analysis (SRA).

The most recent reliability forecast was made available in real-time to help with the health management of products and systems based on deterioration data collected in the actual environment. Researchers have utilized hazard analysis to assess the dependability of systems and individual components. For example, Sulaman *et al.* (2014) [195] described their experiences using the System Theoretic Process Analysis (STPA) approach to conduct hazard analysis on a forward collision avoidance system. The author's goals were to analyze the effectiveness of the researched method in terms of the quantity and quality of recognized dangers and time efficiency in terms of the required efforts.

Systems-Theoretic Process Analysis (STPA), a novel hazard analysis technique presented by Ishimatsu *et al.* (2014) [196], can detect potentially dangerous design defects such as incorrect software and system architecture and unsafe interactions between various system components. Field Programmable Gate Array (FPGA) software is the new objective, so Jung *et al.* (2020) [158] suggest a modified procedure and guiding phrases at the software requirement analysis phase in NUREG/CR-6430, adapted for the new target. For a prototype version of an FPGA-based controller in Korea, the authors conducted a

hazard analysis on the FPGA software to demonstrate the viability of the improved procedure and suggested guiding words.

The safety analysis of PLD (Programmable Logic Device)-based safety systems has been the subject of practical methodologies proposed by Da Silva Neto *et al.* (2018) [197] & Vismari *et al.* (2015) [198]. To undertake a safety study on the PLD, they employed HDL descriptions written in a hardware description language (HDL). The evaluation of threshold-based Early Warning Systems (EWS) for natural hazards was provided in a framework by Martina *et al.* (2015) [199]. The Probability of Detection (POD) and Probability of False Alarms (PFA) were the traditional measures of system reliability. The authors showed how the POD and PFA might be used to establish the EWS efficacy, a measure of risk reduction.

Using feedback transmission for manual Control Action (CA) generation, Shin *et al.* (2021) [200] suggested a method to analyze Instrumentation & Control (I&C) system dangers and evaluate the relative relevance of system components. An opportunistic maintenance strategy was suggested by Najafi *et al.* (2021) [201] for sustaining mechanical systems made up of two economically dependent series unit series units that are economically dependent. For Units 1 and 2, age data and condition monitoring, respectively, are accessible. Condition monitoring data are used to determine the hazard rate of unit 1's stochastic degradation using the Proportional Hazards Model (PHM). Unit 1's stochastic deterioration is described by a gamma process.

As a function of their performance during and after the multi-hazard, Cheng *et al.* (2021) [202] discussed the resilience quantification of engineered systems and Critical Infrastructures (CIs). To account for the uncertainty of the hazard and recovery resource availability, stochastic performance metrics such as availability and recovery time are investigated across time and adopted to quantify resilience as a piecewise function. Regarding system reliability measures, the quality of resilience is carefully examined. Zheng *et al.* (2021) [203] conceptually presented a reliability-based methodology for constructing new buried pipes or appraising existing pipes deployed in fault zones. Bensaci *et al.* (2023) [187] explore the capacity to employ complicated multi-mobile robotic systems in dangerous and dynamic contexts, such as industrial plants and laboratories, with the human factor present.

2.6. Reliability Block Diagrams (RBD)

A reliability block diagram is a network of system elements connected by their logical reliability relationships. Each component is represented by a box that can either be considered to be functioning or to be malfunctioning. As shown in Figures 2, 3, 4 and 5, which illustrate RBDs for series, parallel, and "bridge" systems, respectively, this model enables the examination of the impact of component failures on various system topologies (De Vasconcelos *et al.*, 2018) [204]. The reliability block diagram (RBD), which considers the physical placement of the system's components, is frequently used to study the impact of item failures on system availability (Vanderley *et al.*, 2019) [205].

To analyze the reliability of binary cold-standby systems, Wang *et al.* (2012) [206] proposed an approximation model based on the central limit theorem. An algorithm for assessing the performance distribution of intricate series-parallel multi-state systems with common cause failures brought on by the propagation of system element failures was presented by Levitin & Xing (2010) [207]. An enhanced single-pass method for digital combinational circuit reliability analysis was introduced by Seyyed & Mohammadi (2011) [208]. LV *et al.* (2012) [209] presented a framework for conducting analogue reliability simulations, enabling reliability to be addressed as early as the design phase.

They also proposed a statistical model of Negative bias temperature instability (NBTI), which encompasses all the fluctuations resulting from circuit use conditions. A strategy for "Design for Reliability" in solid-state lighting (SSL) was presented by Tarashioon *et al.* (2012) [210]. The foundation for comprehending LED supply chain

dependability challenges was laid by Chang *et al.* (2012) [14]. The thermal shock test, electrical service life test, and isothermal ageing test were carried out using small outline transistor (SOT) devices manufactured by Tian *et al.*, (2011) [211] using commercial epoxy moulding compound (EMC) encapsulation and fine copper wire bonding technology. System reliability assessment (SRA) was formulated as a Bayesian network (BN) problem by Zhong *et al.* (2010) [212], considering parameter uncertainty.

A model to evaluate the reliability of helicopter MGB lubrication systems was presented by Rashid *et al.* (2015) [213]. A multi-physics reliability simulation technique for solid state lighting (SSL) electrical drivers was presented by Tarashioon *et al.* (2014) [214]. Li *et al.* (2015) [215] presented a novel use of percolation theory to examine a network's reliability. A reliability database is required to apply a model-based description of the failure modes and dysfunctional behaviours of components, as stated by Cressent *et al.* (2013) [216]. An approach for evaluating the dependability of sensors in multi-sensor control systems was presented by Łęczycycki *et al.* (2015) [217]. An approach for modelling the reliability of systems with correlated identical components—i.e., components that have the same reliability and share a failure correlation parameter—was proposed by Fiondella & Xing (2015) [218].

Fink *et al.* (2014) [219] suggest the application of multilayer feed-forward neural networks based on multi-valued neurons (MLMVN), a particular kind of complex-valued neural network, to time series-based reliability and degradation prediction problems. To shorten correction times and increase field programmable gate array (FPGA) reliability, a unique built-in error correction code (ECC) employing encode-and-compare of the data and parity bits was developed by Ahilan & Deepa (2015) [220]. Johansson *et al.* (2013) [76] aimed to compare and contrast vulnerability analysis and reliability analysis, two methods for analyzing key infrastructures and the kinds of findings they produce.

Using Petri net modelling, Liu & Rausand (2013) [221] investigated the effects of the three testing methodologies on a safety-instrumented system (SIS) subsystem consisting of two identical channels that receive a 1-out-of-2 vote, under varying demand rates. The integrated importance measure (IIM) was expanded by Si *et al.* (2013) [222] to quantify the impact of a component residing at a particular state on the overall performance of the multi-state systems. Zhu *et al.* (2014) [223] concentrated on substrate charge injection, a novel line of inquiry into leakage current.

The difficulties in forecasting the dependability of power electronics converter systems were discussed by Schuderer *et al.*, (2023) [224], who also offered suggestions. A virtual qualification-based methodology for System-in-Package (SiP) reliability assessment was presented by Guan *et al.* (2023) [225]. Hsieh *et al.* (2023) [226] look into and offer a machine error tolerance-based approach for reliable evaluation and cost-effective memory protection for machine learning systems. To evaluate the dependability of a multi-parameter monitoring system for Intensive Care Units (ICUs), de Araujo *et al.* (2022) [81] created a modular and parametric model.

Binary decision diagrams (BDDs) are used by Feng *et al.* (2022) [227] to assess the dependability of a signal unmanned aerial vehicle (UAV) from the standpoint of system composition. A wind turbine fitted with a 2 MW direct-drive permanent magnet synchronous generator (PMSG) was used as a case study by Ye *et al.* (2020) [228]. Chen *et al.* (2020) [229] proposed a hierarchical model based on the binary decision diagram (BDD) to integrate four types of damage accumulation rules into PMS reliability modelling, including the inhomogeneous failure mechanisms that have the same damage effect in one phase or different phases and the homogeneous failure mechanisms that have a combinational profile or phase constant stress. Mi *et al.* (2020) [116] introduced a methodical approach to reliability assessment that utilizes the notion of survival signature to evaluate the dependability of intricate systems that consist of several component kinds.

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Kaczor et al. (2016) [230] proposed an application of Monte Carlo simulation and Reliability Block Diagram (RBD) methods for a comparative examination of the safety integrity level. Signoret et al. (2013) [231] address the graphical features of Petri Nets (PNs) and first suggest some incredibly basic tips and guidelines organize and enhance the drawing of typical PNs. It describes how predicates and assertions enable constructing modules (i.e., generic sub-PNs) to construct PNs in a modular manner.

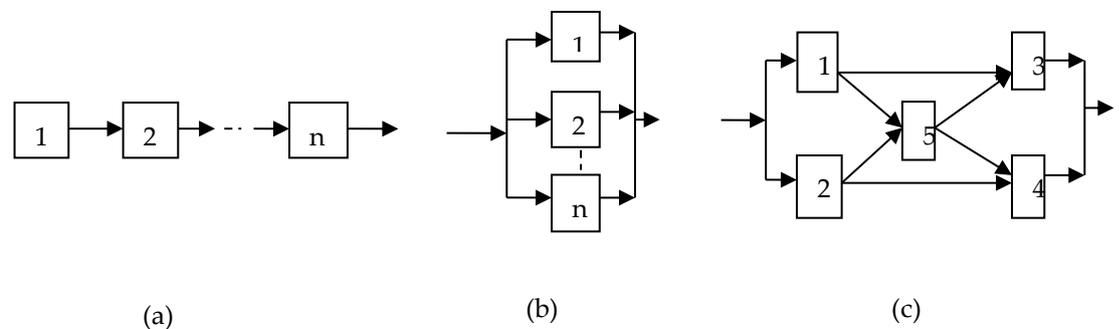


Figure 2. Reliability block diagram for series (a) parallel (b) and “bridge” (c) systems.

Using a Reliability Block Diagram (RBD) to model system degradation, Ding et al. (2017) [232] suggested a novel method for Safety Integrity Level (SIL) verification of Safety-Related Systems (SRS) with diversified redundancy. Using RBD and FT methodologies, Vanderley et al. (2019) [205] conducted reliability evaluations of Emergency Diesel Generators (EDGs) of Nuclear Power Stations (NPPs). There are many different qualitative and quantitative assessments possible because each technique has advantages and downsides. Hasan et al. (2015) [233] presented a succinct overview of the various RBD analysis approaches that are currently available and compare them in terms of accuracy, user-friendliness, and processing requirements.

For Category 1 equipment, Childs et al. (2018) [234] created a brand-new reliability technique based on the Reliability Block Diagram (RBD) and Petri Net. The RBD focuses on demonstrating how various component failures could impact the equipment's subsystems and how those failures could result in a system failure overall. Mohsenian et al. (2023) [235] investigated the impact of acceleration-sensitive non-structural components on the overall seismic reliability of the structure. Jia et al. (2019) [236] suggested a new solution approach based on a Dynamic Uncertain Causality Graph (DUCG) and added a common cause failure block to the Dynamic Reliability Block Diagram (DRBD). Recheda et al. (2021) [237] built and analyzed the RBD for the Collective Thomson Scattering (CTS) front-end, both in terms of function and impact on ITER tokamak operations.

2.7. Failure Modes and Effects Analysis (FMEA) and Failure Mode, Effects and Criticality Analysis (FMECA)

FMEA (Failure Modes and Effects Analysis) and FMECA (Failure Modes, Effects and Criticality Analysis) are procedures created to pinpoint probable failure modes for a

process or product before issues arise and to evaluate the risk. Although performing an FMEA on already-existing items or processes might be beneficial, it is ideal to do so during the product design or process development stages (Lipol & Haq, 2011) [238]. Several articles have been written about choosing a maintenance strategy, including literature reviews by Shafiee (2015) [239] and Velmurugan & Dhingra (2015) [240], both of which highlight the reliability-centered approach as one of the most widely utilized methods.

In an experimental study, Mattila *et al.* (2012) [241] assessed the effects of package temperature on the drop reliability of electronic assemblies using the finite element approach. A method that uses a cascade diagram to look at interdependencies along with reliability and contingency analysis (power flow) of power systems was presented by Kjølle *et al.* (2012) [242]. A framework for establishing a broad approach to Failure Process Modeling (FPM) was introduced by Regattieri *et al.* (2010) [164]. Yang *et al.* (2012) [243] developed a new approach for predicting long-term reliability that uses a new linear elastic parameter, dw/dT . A multi-objective, multi-dimensional mixed 0-1 knapsack model and a broad framework for preventing child injuries were created by Bas (2011) [244] to ascertain the best time to implement preventative measures against child injuries.

Zaghloul *et al.* (2011) [245] examined the state-of-the-art understanding of the dielectric charging and stiction critical failure processes in electrostatic micro- and nano-electromechanical systems (MEMS and NEMS). Chen *et al.* (2012) [246] suggested an electrical analysis-based detecting approach for the manufacturing of valveless peristaltic lead zirconate titanate (PZT) micropump. The impact of epoxy moulding compound (EMC) curing throughout its lifetime on package reliability was examined by Noiijen *et al.* (2010) [247]. Stochastic Petri nets (SPN) were applied to determine the availability of safety-critical on-demand systems by Kleyner & Volovoi (2010) [248]. Vaurio (2010) [132] presented an effective ranking system for important measurements and created several new metrics about configuration control, fault diagnostics, system failure count, and system failure intensity.

Karppinen *et al.* (2012) [249] looked into the loading conditions created on handheld device component boards during both product-level and board-level drop testing. According to Kim *et al.* (2013) [250], a mission-critical system, like a nuclear, aeronautical, or chemical system, can benefit from a reliability allocation problem in its early stages of development. Jacob (2015) [5] presented a method for enhancing the identification of the underlying cause of electronic component failures through the application of a system-related failure analysis technique. Wang *et al.* (2015) [251] proposed a multiphysics modelling approach to assess the interactive effects of failure mechanisms on actuators. The process involves pre-analyzing potential failures through the FMMEA (Failure Modes, Mechanisms, and Effects Analysis) tool, which guides the electro-thermo-mechanical-reliability modelling process.

Yadav & Zhuang (2014) [252] examined the shortcomings of the current methodologies and suggested a modified criticality measure for assigning subsystems to system-level reliability improvement objectives. A succinct reliability analysis of network security deriving from queuing, reliability, and stochastic modelling theories was presented by Kondakci (2015) [253]. An approach for evaluating reliability that takes into account the correlativity of failure mechanisms—which include accumulation, competition, acceleration, inhibition, and trigger—was given by Chen *et al.* (2015) [254]. According to Musallam *et al.* (2014) [255], under anticipated in-service and qualification test settings, the wear-out rates and life consumption for the primary failure mechanisms were quantified by combining a reduced-order thermal model with life models based on the physics of failure.

The classic FMECA (Failure Modes, Effects and Criticality Analysis) approach was extended by Oguz *et al.* (2018) [256] to take human aspects into account while analyzing accessibility/repairability, contact likelihood, and degree of contact. To address the epistemic uncertainty that frequently affects input evaluations on risk parameters, Certa

et al. (2017) [257] presented the Dempster-Shafer Theory (DST) of evidence as an appropriate mathematical framework. A stress and deformation analysis was presented by Li et al. (2018) [258] to investigate the failure mode of the suspended inductors under shock. A general model explaining the functional relationship between the three risk priority number (RPN) elements was proposed by Kim & Zuo (2018) [259]. Failure Mode and Effect Analysis (FMEA) is one of the most popular methodologies for identifying the causes and effects of failures.

Catelani et al. (2018) [260] focused on failure analysis using two techniques developed from FMEA: Failure Mode, Effect and Criticality Analysis (FMECA) and Failure Modes, Mechanisms and Effect Analysis (FMMEA). According to Abrahamsen et al. (2016) [261], the conventional Healthcare Failure Mode and Effect Analysis (HFMEA) has to be modified in a few ways. In their assessment of the major failure reasons of Micro-electro-mechanical System (MEMS) goods, Li et al. (2016) [262] suggested a novel correlative model for assessing the dependability of MEMS products. The dependability of a flexible spacecraft's attitude control subsystem (ACS) in low earth orbit (LEO) was examined by Damircheli et al. (2020) [263].

Tsai et al. (2016) [264] compared the experimental findings with the finite element simulation related to measurements of aluminium nitride (AlN) strength and the thermal deformation of Cu/AlN bi-material plate to assess the dependability of the through-aluminium-nitride-via (TAV) substrate. To assess the state-probability and reliability of a multi-state system, Li et al. (2017) [265] offered a combination method that makes use of both a binary decision diagram (BDD) and a multi-state multi-valued decision diagram (MMDD) model, while also accounting for the failure mechanism correlation. The study conducted by Oberhoff et al. (2016) [266] investigated the use of high-frequency scanning acoustic microscopy in the examination of Micro-electro-mechanical System (MEMS) sensors.

An & Sun (2017) [267] created a reliability model for a complex system that undergoes several interdependent competitive failure processes when shock loads beyond a specific threshold; only shock loads exceeding this threshold in magnitude can cause abrupt degradation increments. Thermal Laser Stimulation (TLS) applies to failure analysis in powered devices by Helfmeier et al. (2016) [268], who also highlight its significant advantages. A ceramic NTC (negative temperature coefficient) thermistor's possible weak areas were described, and Jeong et al. (2017) [269] estimated how long the part will last in a laser printer.

Yaqun et al. (2020) [270] offered a reliable and effective method for assessing the thrust chamber reliability of reusable rocket engines. They also measured the significance ranking of geometrical dimensions, material properties, and working loads for chamber reliability. This information offers important insights into the reliability-based design and optimization process for reusable rocket engines. A time-variant reliability solution utilizing a Kriging model was proposed by Qian et al. (2020) [271] for an industrial robot rotate vector (RV) reducer with numerous failure sources. Kowal & Torabi (2021) [272] objective was to determine how frequently the High-Temperature Engineering Test Reactor has unscheduled outages as a result of Electrical Facility problems.

A consensus and opinion evolution-based FMEA strategy was presented by Zhang et al. (2021) [273] for reliability management in uncertain situations and social networks. The standard ways of creating aluminium nitride (AlN) ceramic substrates—thin-film, thick-film, and directly bonded copper approaches—were examined and contrasted by Hung & Chen (2019) [274]. A new sliding window mechanism with two failure criteria was creatively proposed by Lu et al. (2019) [275]. A modified accelerated reliability growth model was presented by Wang et al. (2019) [276] for newly repairable devices that are offered with a two-dimensional warranty. Different strategies were suggested by Eslami Baladeh & Taghipour (2022) [277] to deal with the unpredictability of working situations in redundancy allocation difficulties.

The reliability assessment technique for electromagnetic relays was examined by Xiang *et al.* (2023) [278]. To identify critical failures of floating offshore wind turbines with linked failures, Sun *et al.* (2023) [279] introduced a novel failure mode and effect analysis schedule called correlated-Failure Mode and Effect Analysis (FMEA). Sajaradj *et al.* (2019) [280] identified the failure mode and effect analysis as one of the key frameworks used in reliability - centred maintenance in their literature review that only addresses this topic. The core of the dependability techniques is the examination of various failure modes and their potential repercussions. The majority of reliability-centred approaches may be linked back to the FMEA approach, even if the specific technique utilized by maintenance workers does not go by the name of FMEA (Sajaradj *et al.*, 2019) [280].

Scheu *et al.* (2019) [281] and Lipol & Haq (2011) [238], respectively, summarize the addition of a criticality analysis to the FMEA in their articles. The maintenance team can respond to the most upsetting failures first thanks to the so-called failure mode, effects and criticality analysis (FMECA), which ranks the identified failure modes according to failure rate and severity. Before reaching the failure analysis, the FMEA or FMECA often includes a preparation phase and a structure and function analysis. Each potential failure mode's detection rate, effect severity, and chance of occurrence are all defined in the failure analysis (McDermott *et al.*, 2013) [282]. Often the detection rate is not taken into consideration while making maintenance plan decisions (Lopez & Kolios, 2022) [283]. Each failure mode's occurrence, severity, and detection are individually represented by an ordinal scaled value that, when multiplied, yields the failure mode's risk priority number.

The method's various advancements are outlined in Sharma & Srivastava's (2018) [284] literature analysis on FMEA implementations. Only one of the 67 publications examined discusses the possibility that failure probability can vary over time. Another state-of-the-art study on FMEA/FMECA from 2017 summarizes recommendations for addressing widespread criticism in Spreafico *et al.* (2017).s [285] report. Peyghami *et al.* (2019) [286] suggested the failure Mode, Effects and Criticality Analysis (FMECA) method assess the significance of converters in Power Electronic based Power Systems (PEPSs). A power system risk measure predicts the failure modes' impacts and uses contingency analysis to categorize them.

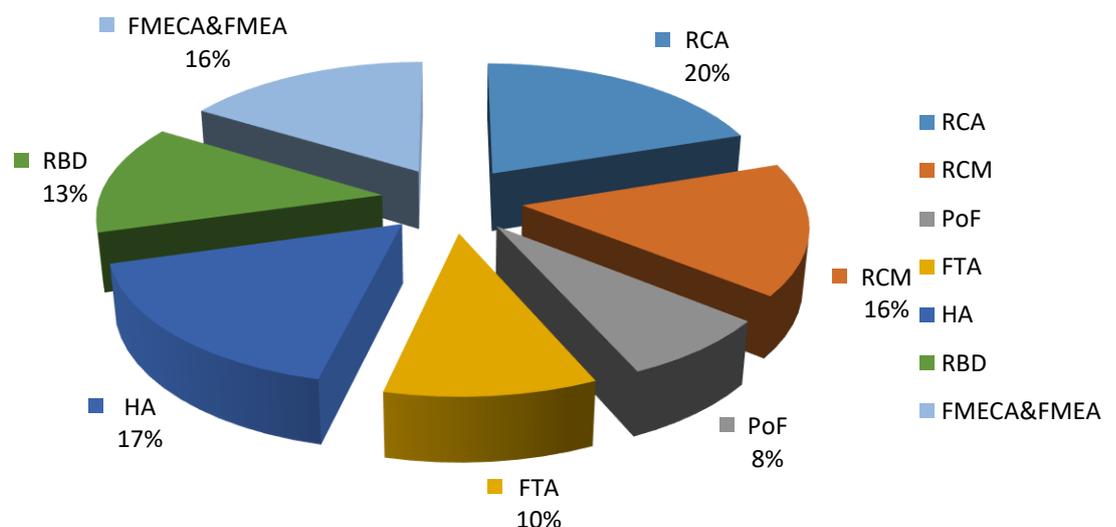


Figure 3. Percentage of reliability techniques reviewed.

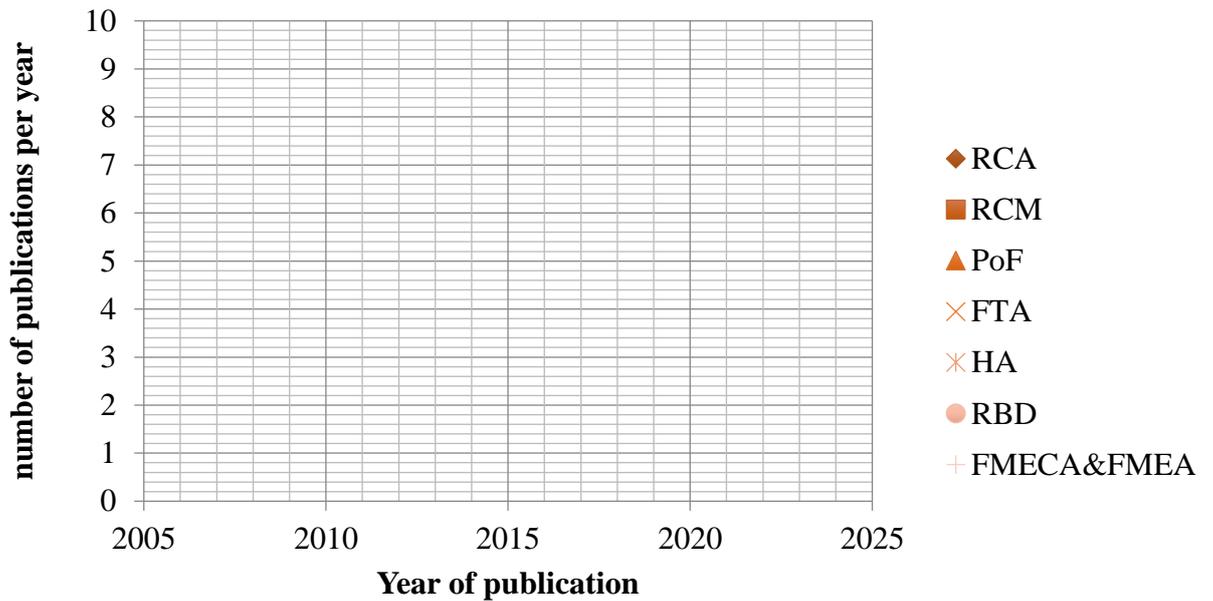


Figure 4. Review of the evolution of reliability techniques from 2010 to 2023.

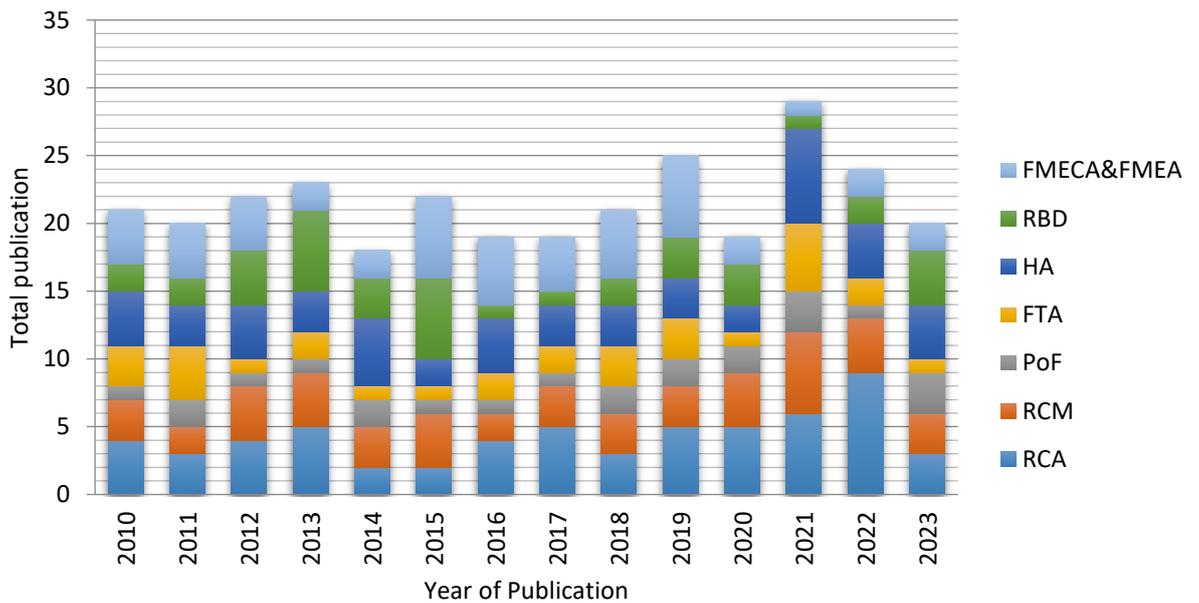


Figure 5. Total number of reliability techniques reviewed per year from 2010 to 2023.

3. Conclusion

The proportion of reviewed papers using either RCA, RCM, FMEA/FMECA, FTA, RBD, RCM, PoF, or Hazard analysis to increase the reliability of PLCs. RCA, which makes up 20% of the publications analyzed, has been used the most to increase system reliability, followed by HA, RCM, RBD, FTA, and PoF, which account for 17%, 16%, 16%, 13%, 10%, and 8% of the articles reviewed, respectively. A scatter chart depicts the development of reliability techniques from 2010 to 2023. The use of RCA, HA, (FMECA and FMEA) and RCM is on the rise.

This upward trend can be attributed to the fact that RCA is the primary method used by maintenance and reliability engineering specialists to address problems that affect an

organization's capacity to achieve strategic goals and is a method for identifying potentially dangerous system components, while HA assists in methodically locating and recording possible risks or modes of failure that could jeopardize a system's dependability. It enables a thorough analysis of the system, taking into account numerous variables that could cause problems. (FMECA and FMEA) are procedures designed to identify likely failure modes for a product, and RCM is a highly effective and useful methodology for carrying out plans of preventive and predictive maintenance tasks.

In addition, alternative methods with lower percentages have advantages as well, such as RBD, which takes into account the physical arrangement of the system's components and is widely used to analyze how item failures affect system availability. FTA transforms a physical system into a logical diagram, making it one of the industry's most well-liked techniques for calculating safety and reliability, while PoF uses knowledge and comprehension of the mechanisms and processes that cause failure to forecast reliability and improve product performance, while. Using stacked bars, the annual total number of reliability approach publications from 2010 through 2023. It was evident that RCA has been most frequently utilized to enhance system reliability analysis.

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