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Maintenance, Repair, and Overhaul: A Preview

1.1 Introduction

To undertake the reliability analysis of repairable systems, most of the industries establish their own setup of maintenance, repair, and overhaul (MRO) facilities. Before we embark upon the remaining contents of the book, the authors thought it imperative to introduce the readers to the basics of maintenance, repair, and overhaul. This chapter provides a preview of the fundamental understanding of MRO so that it will be easier to assimilate the comprehension of the advanced reliability techniques to deal with repairable systems, which has been endeavored in this book.

Maintenance, repair, and overhaul, or MRO, provides life cycle maintenance through routine preventive maintenance, planned out-of-service maintenance, or (corrective) repairs, overhaul, or rebuilds for damaged equipment. Even though industries account for the majority of them, a product or piece of equipment with high costs and a long lifespan is definitely a candidate for MRO services. Examples include massive manufacturing machinery, electric power generation, marine boats and infrastructure, mass transit vehicles, military vehicles, and systems.

Industrial systems generally deteriorate over time due to use and exposure to environmental factors. This deterioration eventually results in system failure, which in turn causes safety problems, equipment damage, quality problems, and unplanned machine downtime. A few decades ago, maintenance was mainly thought of as something challenging to manage and had to be done after a failure. Maintenance is widely acknowledged as a crucial component of asset management and a crucial commercial function. Organizations are becoming more aware of how maintenance intervention planning may increase their productivity and reliability. Preventive maintenance activities increase as a result and better fit with other business processes like production scheduling and spare parts management.

Garima Sharma and Rajiv Nandan Rai. Advanced Techniques for Maintenance Modeling and Reliability Analysis of Repairable Systems, (1–36) © 2023 Scrivener Publishing LLC

For instance, companies in the process and chemical sectors can significantly boost profitability by preventing unscheduled stoppages. The continuous automation of production processes and an intensifying level of competition in the market have increased awareness of the need for good maintenance planning.

Keeping facility equipment, tools, and infrastructure in good condition and operating them efficiently is the objective of anybody who works in maintenance. This helps to prevent unanticipated downtime or equipment failure. This is what repair and maintenance allow us to do. Although the terms repair and maintenance are sometimes used interchangeably, they have various meanings in the asset management industry. When an asset breaks, is damaged, or ceases to function, repairs are restorative work that must be done. Routine tasks and/or corrective or preventive repairs performed on assets to avoid damage and extend life expectancy are referred to as maintenance. Examples include routinely cleaning grease traps, and air conditioning units, painting, and inspections.

An overhaul is a general maintenance procedure carried out on a piece of machinery or other industrial equipment. The purpose of an overhaul is to maintain the system's function. Regular inspections can stop a variety of critical damage. Typically, maintenance service providers carry out machinery overhauls. It is possible to agree on the frequency of overhauling; regular maintenance is typically planned for once a year. A more frequent equipment check is advised for older machinery, especially larger ones with complicated mechanics. Typically, overhauls begin with a thorough inspection. The overhauled machine is examined by skilled maintenance personnel. It indicates that the machine's operation is tracked while it is in use. The item of equipment should be disassembled following the initial inspection. For additional inspection and the subsequent overhauling stages, such as repair, disassembly is essential. An efficient machine breakdown by a trained maintenance technician can reveal which equipment components require replacement or repair. The machine is either fixed or certain damaged parts are changed, depending on the problem. This procedure demonstrates once more how efficient overhauling is compared with complete equipment replacement.

Since the spare parts may need to be acquired from a manufacturer, part replacement may require more time than a straightforward repair. Reassembling the entire mechanism is done after the successful substitution of spare parts. The reassembly, which comes last, is essential to the equipment's operation. Reassembly requires a certain level of competence; therefore, it is best left to the experts. It is difficult to determine whether a repair was successful without testing. Testing determines if the reassembly is successful or not; otherwise, the procedure restarts at the beginning (inspection).

In the further section, a brief understanding of the maintenance, repair, and overhaul is provided for the benefit of the readers, and the same is further amplified in the next chapter as per the subject covered in subsequent chapters.

1.2 Maintenance

Maintenance is an essential integral of any organization. It is far beyond just fixing a failed system. It is an investment for the future and guarantees that the system will continue to perform reliably. It is defined as "Maintenance is a philosophy to utilize all physical sciences with a disciplined manner at all levels of the operation, which assures that critical capital asset will provide long-term and reliable performance." Taking such a narrow perspective, maintenance activities will be confined to the reactive tasks of repair actions or item replacement triggered by failures. Thus, this approach is known as reactive maintenance, breakdown maintenance, or corrective maintenance. "All operations aimed at keeping an object in, or restoring it to, the physical state considered necessary for the performance of its production function" is how Geraerds (1983) described maintenance in a more modern context. Of course, proactive actions like routine maintenance, periodic inspections, preventive replacements, and condition monitoring are also included in the scope of this expanded view.

Depending on how duties are distributed within the business, these maintenance activities may be split among different departments. For instance, in a company that uses total productive maintenance (TPM), the maintenance department handles significant repairs and overhauls, while the operating staff is in charge of routine service and periodic equipment inspection (Nakajima, 1988). The actual maintenance procedure may be exclusive to a particular facility, industry, or collection of issues. Identical product organizations may use different maintenance systems with varying levels of technological development and production size, and the various systems may function effectively. As a result, maintenance systems are created employing formal decision-making tools and processes along with experience and judgment. However, two important factors should be taken into account: a strategy that determines which level of the plant to perform maintenance on, thus outlining a structure that will support the maintenance, and second, planning that deals with daily decisions on what maintenance tasks to perform and providing the resources to carry out these tasks. One of the fundamental and essential elements of the maintenance is the maintenance management function (MMF). According to Figure 1.1 below, the MMF entails organizing, planning, controlling, and implementing maintenance activities.

There are significant factors that must be taken into account while designing the maintenance organization. The factors to consider are maintenance capacity, centralization versus decentralization, and insourcing versus outsourcing maintenance. The following aspects or factors significantly impact a maintenance organization's role within the plant or the entire organization:

- Type of business: such as whether it is labor-intensive, high-tech, producing goods, or providing services.
- Goals: These could include things like maximizing profits, expanding market share, and other industries' goals.
- Size and organizational structure.
- Organizational culture and the scope of the maintenance responsibilities assigned.

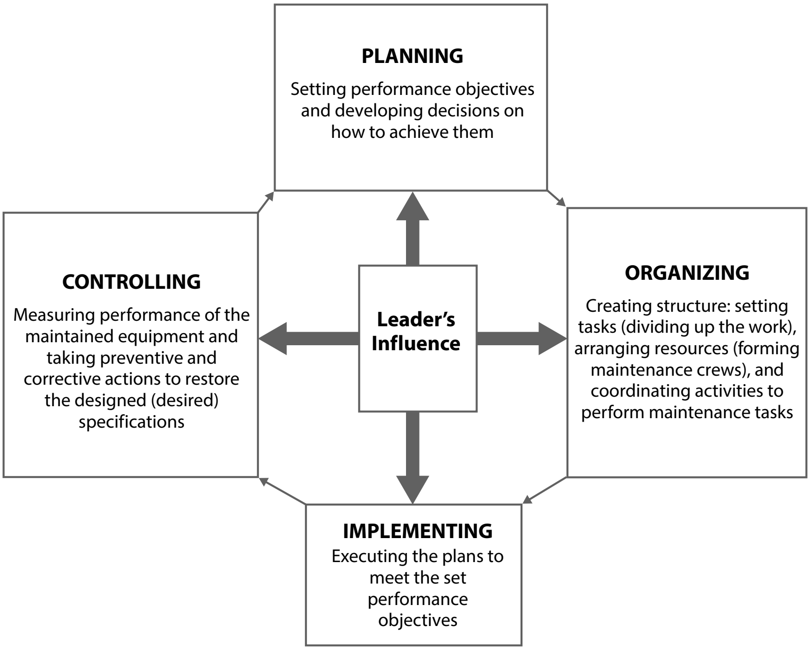

Figure 1.1 Activities in maintenance management function.

Maintenance expenses make up a sizeable amount of operating expenses for many asset-intensive enterprises. In larger businesses, a $1 million reduction in maintenance costs generates the same amount of profit as a $3 million increase in sales (Wireman T, 2007). Around 1,500 billion euros are spent annually on Europe's maintenance budget (Altmannshoffer R, 2006) and 20 billion euros per year for Sweden (Ahlmann H, 2002). In opencut mining, a typical dragline's loss of revenue ranges from US $0.5 to US $1 million per day. A 747 Boeing plane's loss of revenue ranges from US $0.5 to US $1 million per day (Murthy, Atrens, and Eccleston, 2002). As a result, business management is increasingly aware of the value of maintenance productivity.

Here are a few instances where inadequate maintenance procedures led to catastrophes and accidents that resulted in significant losses, including Bhopal, Piper Alpha, the Columbia space shuttle, and power outages in 2003 in New York, the UK, and Italy. Instead of saving a billion US dollars, such an accident may have been avoided and improved the organization's reputation. Maintenance performance monitoring has become a crucial component of strategic thinking for the manufacturing and service sectors. In order to oversee and monitor the maintenance process' performance, necessary and corrective steps must be taken to reduce and mitigate safety-related risks, uphold societal obligations, and improve the effectiveness and efficiency of the asset being maintained.

Maintenance performance is a metric frequently used by enterprises to gauge maintenance productivity. The ratio of a production system's output (the products or services delivered) to its input (the labor, materials, tools, plant, and equipment, among other things used to produce the products or services) is generally understood to be the definition of productivity. Reducing the amount of maintenance materials used as well as projects, outages, and overhaul costs would increase maintenance productivity (Wireman T, 2007). Optimizing maintenance resource use and boosting maintenance productivity are two ways to lower operation and production expenses (Duffuaa and Al-Sultan, 1997). In order to evaluate, monitor, control, and make suitable and timely decisions, evaluating maintenance productivity performance is essential for any production and operating firm.

What to measure, how to communicate maintenance performance throughout the business, and how to tie maintenance performance to goals and strategies are some of the issues that need to be clarified while creating maintenance metrics (Murthy, Atrens, and Eccleston, 2002). To achieve this, it is necessary to aggregate measured maintenance performance indicators, such as availability, reliability, and mean time between failures, from the shop floor level to the strategic levels for making management decisions. This basically entails breaking down the corporate objectives into measurable targets up to the shop floor level (A. H. c. Tsang, 2002).

The performance measurement needs to be viewed along three dimensions (Andersen B and Fagerhaug T, 2007), i.e.,

- Effectiveness,
- Satisfaction of customer needs,
- Efficient, economic, and optimal use of enterprise resources,
- Changeability—strategic awareness to handle changes.

The effectiveness of the plant's operations is significantly influenced by its maintenance practices and safety record. To satisfy supply deadlines, costs, quality standards, and quantity requirements, management must rely on the anticipated plant capacity. To reach ideal production levels, a suitable maintenance and safety approach must be modified. Some of the essential measures of maintenance productivity are the total cost of maintenance/total production cost, availability, production rate, quality rate, mean time to repair (MTTR), mean time between failures (MTBF), maintenance breakdown severity, maintenance improvement, maintenance cost per hour, manpower utilization, manpower efficiency, material usage/work order, and maintenance cost index.

Maintenance performance indicator (MPIs) are used to assess maintenance effectiveness (Wireman T, 1998). A product of numerous measurements is an indicator (measures). A performance indicator is a measurement that can produce a quantitative number to show the degree of performance while accounting for one or more aspects. In addition to many other uses, MPIs could be used for financial reporting; employee performance reviews; customer satisfaction surveys; health, safety, and environmental (HSE) ratings; and overall equipment effectiveness (OEE). In reliability maintenance studies, statistics and probability are essential tools.

In maintenance engineering, failure, function, and functionability of the system are important terms to understand. Failure is an event whose occurrence results in either loss of ability to perform the required function or loss of ability to satisfy the specified requirements. In other words, it is the inability to fulfill any of the component functionability. Functionability is defined as the inherent ability to perform a required function with specified performance and attributes when it is utilized as specified. Function is related purely to the function performed, whereas functionability takes into consideration the level of performance achieved. During its operational life, a restorable system that fluctuates between states of failure and

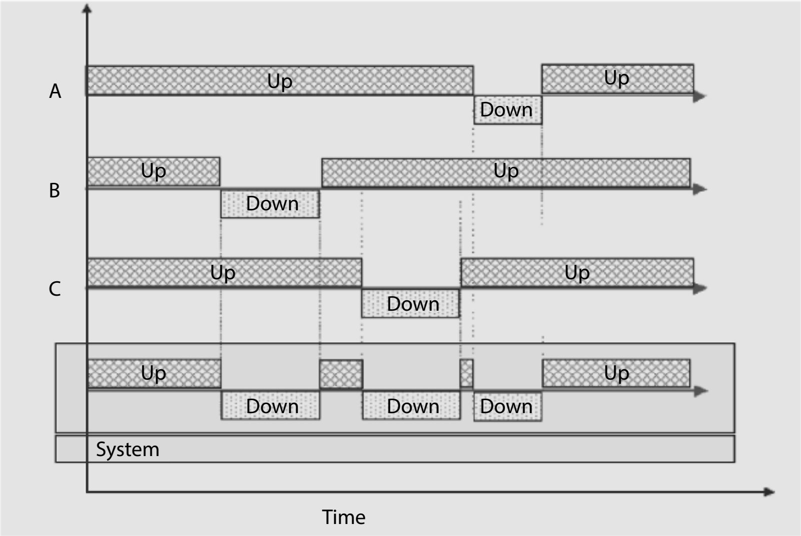

Figure 1.2 Example of a functionability profile in a series system.

function, an established pattern of mapping the states of the system during the utilization process, is known as the functionability profile as shown in Figure 1.2.

The pattern of a system's functionability profile, with a focus on the percentage of time the system in question will be available for functionability fulfillment, is thus one of the key concerns of users of any engineering system. It is obvious that the following two causes are primarily responsible for its particular shape:

1. Inherent characteristics: The decisions made by the designers and builders during the early stages of the system design determine a system's inherent qualities, such as reliability, maintainability, and supportability, which directly determine the frequency of failures, the complexity of maintenance tasks, and the ease of the support of the tasks required.
2. Utilization characteristics: Each user of the system determines its operational characteristics, which are driven by the operational scenario, maintenance policy, and logistics support concept, with the aim of managing the provision of the resources required for the effective completion of all operation and maintenance chores.

As a result, the shape of the functionability profile, which is the outcome of the combined efforts of the producer and users, defines any figure of merit that is used to characterize the effectiveness of any engineering system. The most commonly used metrics for measuring system effectiveness include availability, readiness, reliability, mission reliability, and metrics comparable to these. Availability encompasses three factors: reliability, maintainability, and supportability. Availability is the characteristic that quantitatively summarizes the functionability profile of an item. Availability is the parameter that translates system reliability and maintainability characteristics into an index of effectiveness. So, availability is defined as a measure of the degree to which an item is in an operable and committable state at the start of a mission when the mission is called for at a random point in time.

The physical properties of the system, spare component availability, repair staff availability, human factors, environmental conditions, etc. are just a few examples of the many variables that might impact the length of downtime. Based on the following criteria, downtime can be split into two categories:

- Waiting downtime: The device is currently inoperative but not being repaired at this time. This might be caused by the time it takes to process paperwork, ship replacement parts, etc.
- Active downtime: The equipment is currently undergoing repair during this time and is therefore not used, or to put it another way, active downtime is the amount of time it takes a repair or replacement to be made. Human variables, as well as the equipment's design, have a significant impact on how long the active downtime lasts.

Reliability is the probability/chance and capability of items (parts, components, equipment, subsystem, and system) to perform their intended function without failure for a desired period in specified use conditions (environment). It can be specified, allocated, predicted, designed-in, tested, estimated/predicted, and demonstrated with its maintainability, availability, safety, and quality level in an optimized way. On the other hand, maintainability is expressed as the probability that an item will be retained in or restored to a specific condition within a given period of time when the maintenance is performed in accordance with prescribed procedures and resources.

In maintenance, maintainability design is essential for any organization in steps as shown in Figure 1.3. It begins with defining maintainability

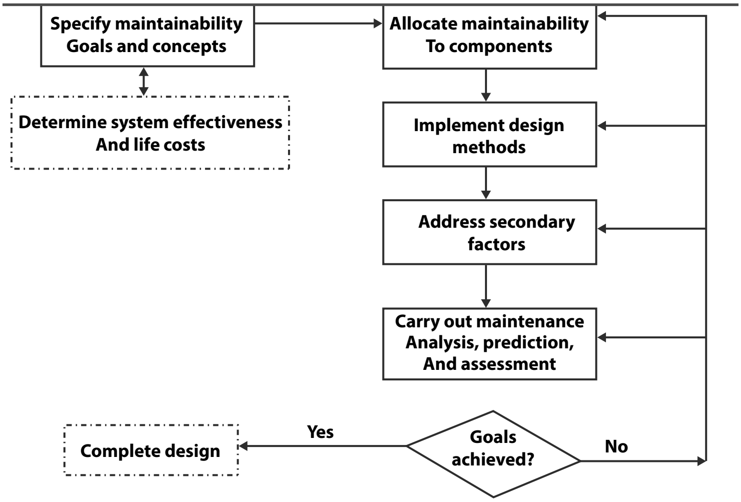

Figure 1.3 The maintainability design process.

goals. The determination of goals coincides with reliability specifications. The overall maintainability goals must be allocated to the repairable subassemblies. The maintainability design methods are applied to achieve the specified maintainability parameters. Secondary considerations that are included in this analysis are quantity and quality of resources. In the assessment of achieved maintainability, additional design activity may be necessary if goals are not attained.

There are several key concepts that should be followed as part of any design activity that supports this repair time reduction:

1. Fault isolation and self-diagnosis
2. Parts standardization and interchangeability
3. Modularization and accessibility
4. Repair versus replacement

The circumstances (that might not be disjoint) during the design, manufacturing, or use which led to the failure and useful information in the prevention of failures or their recurrence need to be recognized. Considering the consequences and liability of failures, it is important to establish reliability acceptance goals that will minimize and limit the occurrence of failures. Tools such as FMEA, FMECA, reliability growth, and reliability validation tests are important to ensure that the goals are integrated with the process and are tracked through the Design Verification Plan and Report (DVP&R). An industry that follows reliability engineering and standards utilizes failure mode and effect analysis/criticality analysis (FMEA/CA) for its product and/or process, where a risk priority number (RPN)-based approach has assumed precedence over the methodology described in MILSTD 1629A as shown in Figure 1.4. A classic RPN is an arithmetic product of three variables, namely, severity (how serious their consequences are), occurrences (how frequently they occur), and detection (how easily they can be detected in the design, process, or service), with the formula RPN = S × O × D. These three factors are constructed according to expert opinion or available data in a point scale of 10 or 5.

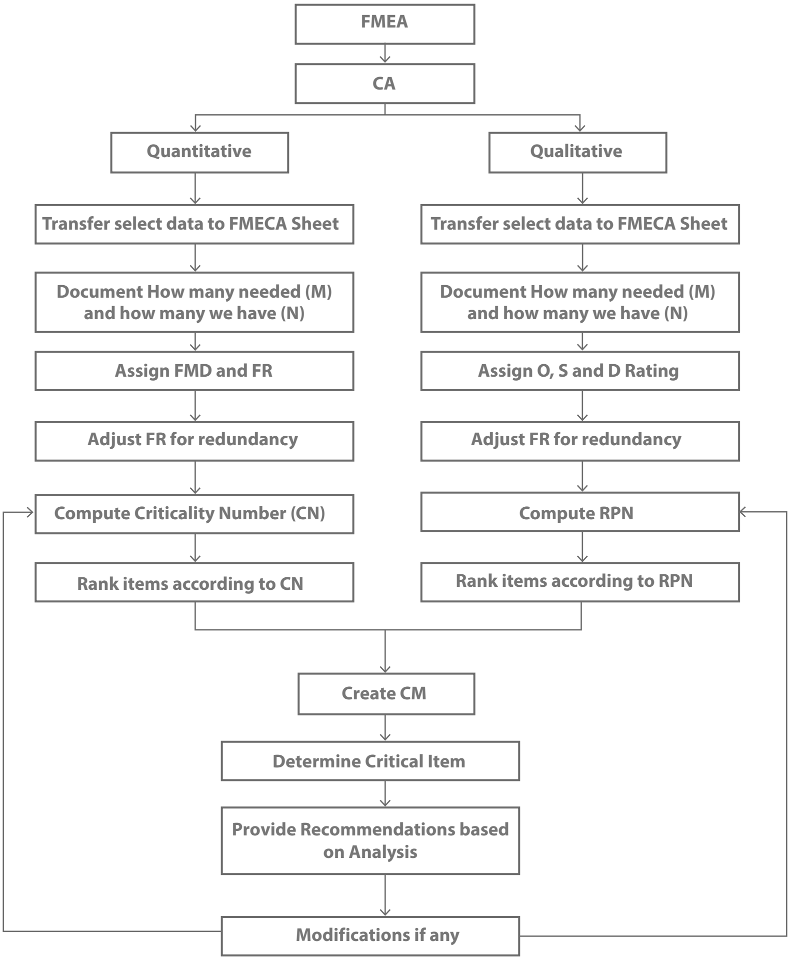

Figure 1.4 Flowchart of the FMEA/CA.

Failure modes refer to the potential failure types or ways. Failures can be possible or actual and include any error or flaws, especially those that negatively impact customers. Effects analysis is the study of the outcomes of those errors. Failures are ranked by the severity of their effects, frequency with which they occur, and ease with which they can be discovered. The goal of the FMEA is to eliminate or reduce failures by initiating action with the failures that have the highest priority, which can be determined by their RPN and/or factor(s). FMEA also records current understanding and actions on failure risks for use in ongoing improvement. FMEA is used in the design phase to prevent failures and, later, for control, both before and during the process operation. The standard FMEA technique has been expanded in a number of ways, but its core principles have not changed.

Reliability engineering is primarily concerned with fixing equipment issues that result in excessive production downtime and maintenance work. Engineering expertise is applied in reliability engineering for risk management, asset life cycle management, configuration management, asset maintenance, and loss prevention. The responsibilities of a maintenance engineer are more tactical, such as ensuring that the assets satisfy the company's current expectations. The maintenance engineer is in charge of day-to-day reliability duties, whereas a reliability engineer considers long-term reliability requirements. To increase the dependability of physical assets in the pursuit of continual improvement, two complementary approaches with various focuses are provided (uptime). These methodologies are as follows:

- Total productive maintenance (TPM)—a people-centered methodology.
- Reliability-centered maintenance (RCM)—an asset-centered methodology.

TPM, which reduces asset failure, production problems, and accidents, offers a thorough life cycle approach to asset management. Everyone in the company is involved, from senior management to production mechanics, production support teams, and external suppliers. The goal is to continuously increase an asset's availability and stop it from degrading so that it retains its optimum efficiency. Three categories, namely, autonomous maintenance, scheduled maintenance, and maintenance reduction, can be used to categorize TPM principles. The purpose of using asset operators autonomously is to carry out some standard maintenance tasks. These jobs involve the regular upkeep of the asset, such as cleaning, inspection, tightening, and lubricating. The maintenance personnel can begin working on proactive asset maintenance by automating some of the routine maintenance operations. The goal of planned maintenance activities, commonly referred to as preventive maintenance, is to replace worn-out parts and restore damaged assets. The maintenance cutbacks asset design and preventive maintenance, which aim to minimize the overall amount of maintenance necessary, make up the TPM idea. To reduce variation, boost productivity, cut maintenance costs, lower inventory, raise training, and improve safety are made possible through total productive maintenance. The suggestions for TPM enhancement include top-down guidance, process integration, and data-driven choices. It can be said that there are mainly eight pillars to achieve TPM as shown in Figure 1.5.

A *reliability-centered maintenance (RCM)* technique is used in reliability-based maintenance. The area covered by RCM includes defining system functions, defining functional and possible failures, exposing failure modes, recording failure impacts and consequences, identifying failure causes, and identifying tasks and activities to reduce the risk of failures and categories of tasks as described in Figure 1.6.

What kind of maintenance activities need to be conducted is determined by RCM, which also provides the answer to the question of what kind of maintenance strategies should be used on an asset. It is still unclear when to carry out the advised maintenance procedure in order to achieve

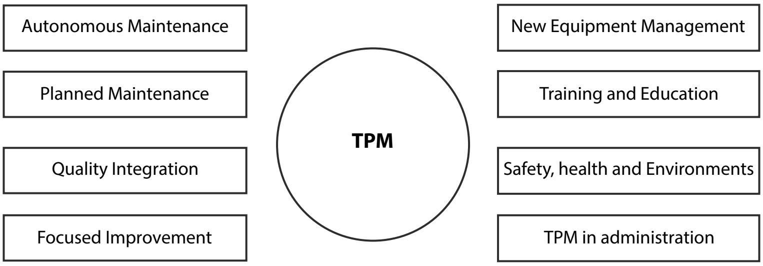

Figure 1.5 The pillars of TPM.

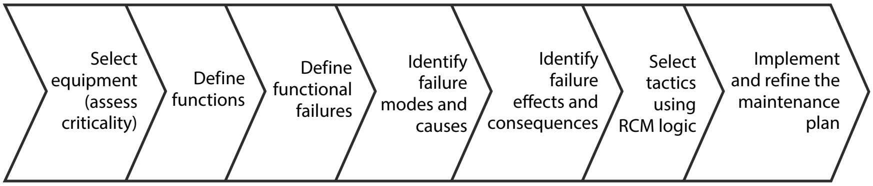

Figure 1.6 The RCM process (Jardine and Tsand, 2005).

optimal outcomes. Asset managers must take into account four crucial decision areas, which are shown as columns in Table 1.1, in order to maximize the life cycle value of the company's people and physical assets. Component replacement is the subject of the first column. Inspection

Table 1.1 Key areas of maintenance and replacement decisions (Jardine and Tsand, 2005).

Optimizing equipment maintenance and replacement decisions			
Component replacement	**Inspection procedures**	**Capital equipment replacement**	**Resource requirements**
1. Best preventive replacement time a) Deterministic performance deterioration b) Replace only on failure c) Constant interval d) Age-based 2. Spare parts provisioning 3. Repairable systems 4. Glasser's graphs 5. Software: SMS and OREST	1. Inspection frequency for a system a) Profit maximization b) Availability maximization 2. A, B, C, D class inspection intervals 3. FFIs for protective devices 4. Condition-based maintenance 5. Blended health monitoring and age replacement 6. Software: EXAKT	1. Economic life a) Constant annual utilization b) Varying annual utilization c) Technological improvement 2. Repair vs. replace 3. Software: PERDEC and AGE/CON	1. Workshop machines/ crew sizes 2. Right sizing equipment a) Own equipment b) Contracting out peaks in demand 3. Lease/buy 4. Software: workshop simulator and crew size optimizer
Probability and statistics (Weibull analysis including the software WeibullSoft)	Stochastic processes (for CBM optimization)	Time value of money (discounted cash flow)	Queuing theory simulation
Database (CMM/EAM/ERP system)			

activities, including condition monitoring, are the subject of the second column. Capital equipment replacement is the subject of the third column. The location of the resources needed for maintenance is the subject of the final column.

Replacement problems (and maintenance problems in general) can be classified as either deterministic or probabilistic (stochastic). Deterministic problems are those in which the timings and outcomes of the replacement actions are assumed to be known with certainty. For example, we may have an item that is not subject to failure but whose operating cost increases with use. Short-term and long-term deterministic models while considering minimum total cost and minimum downtime have been proposed by various authors, for example replacing the air filter in an automobile and overhauling a boiler plant. The timing and result of the replacement action depend on chance in probabilistic problems. In the simplest scenario, the equipment can be categorized as either working properly or not. The time distribution between the completion of the replacement activities and failures may be used to describe the probability law defining shifts from good to failure. Any series of events can be a replacement strategy. On the other hand, the best replacement policies are those that optimize or reduce a particular criterion, such as profit, total cost, and downtime, or guarantee that a specific safety or environmental criterion is not surpassed.

We now provide a glimpse of the concepts related to different types of maintenance for a better appreciation of the readers in this area. However, this book is mainly oriented toward providing advanced techniques on reliability analysis of imperfect maintenance related mainly with preventive and corrective maintenance.

Preventive, corrective, and predictive maintenances are the three typical categories of maintenance actions as shown in Figure 1.7. In order to keep equipment in working order, "preventive maintenance" refers to planned and routine tasks carried out on an operating system according to a set timetable. The term "corrective maintenance" describes procedures carried out as a result of equipment failure with the goal of getting the equipment back to a predetermined operational state. "Predictive maintenance" refers to maintenance tasks that are carried out based on "modern measurement and signal processing systems" condition diagnosis.

Several basic maintenance optimization models include the "age replacement policy" and the "block replacement policy"-based replacement models. These models take into account a technical system that is instantly replaced upon failure by a substitute system, incurring costs of $c > 0$ for each replacement and "penalty costs" of $k > 0$ for each system failure. This system has a lifetime described by a positive random variable T and

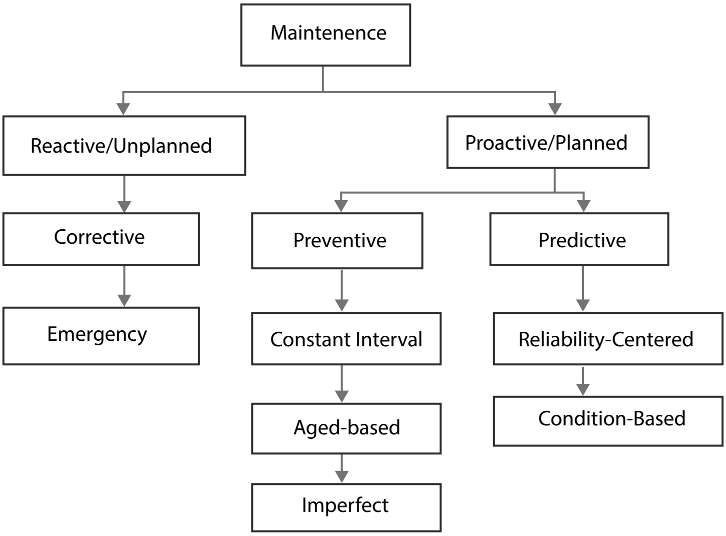

Figure 1.7 Types of maintenance.

a distribution *F*. The "age replacement policy" takes into account a fixed system replacement age that is indicated by a positive constant and aims to reduce the cost per unit of time throughout a series of system lifetimes. The average cost after *n* cycles is derived by dividing the total cost of every additional cycle by the number of additional system lifetimes. By dividing the overall cost per unit time that has occurred until time *t*, the model also takes consecutive cycle costs into account (or the current time). The system is replaced in accordance with this policy when it fails or when it reaches the specified system replacement age, whichever comes first. The "block replacement policy," in contrast, calls for preventive replacements to be carried out at predetermined intervals without taking into account the age of the system's components and at a cost of *c*. At the expense of $c + k$, the system is also replaced when it fails within the predetermined time frames. The block replacement policy, according to the authors, is simpler to manage because system/component replacements take place at predetermined times. The "age replacement policy," on the other hand, is regarded as being more pliable because it considers the system's age.

Jiang (2001) outlines a method for selecting an approximately ideal age-based maintenance strategy for a certain time frame. The ideal replacement age for a unit with a random and undetermined initial age is taken into account by Khatab *et al.* (2017). Dekker and Plasmeijer (2001) take into account maintenance opportunities that appear as a result of a Poisson process. The age replacement strategy is extended by Finkelstein, Shafiee, and Kotchap (2016) to the situation when the system's production is declining over time. The age-based replacement policy, which restricts the timing of preventive replacements to specified dates and times of the year, is introduced by Bajestani and Banjevic (2016). When the age reaches a particular point, these opportunities are utilized. Their model is used in a real-world scenario involving wooden poles in a Canadian electrical company's distribution network. He, Maillart, and Prokopyev (2017) examine the effects of negligent preventive maintenance and take into account the age replacement strategy.

Another area of study looks at defects that can only be discovered by *inspections*, and the key issue is when to conduct these inspections. Finding out the condition of the equipment is the main goal of an inspection. Depending on the state found, additional maintenance steps may need to be conducted once indicators, such as bearing wear, gauge readings, and product quality, which are used to characterize the state, have been specified and inspection was made to identify the values of these indicators. The expenses of the inspection (which will be tied to the indicators used to indicate the condition of the equipment) and the advantages of the examination, such as the discovery and adjustment of minor problems before a severe breakdown occurs, should dictate when the inspection should take place.

Three categories of inspection-related issues are typically looked at:

- Inspection frequencies: for continuously operating machinery that is prone to failures.
- Inspection intervals: for machinery only employed in emergency situations (failure finding intervals).
- Condition monitoring of equipment: optimizing condition-based maintenance (CBM) decisions.

Equipment maintenance and repairs can be expensive, time-consuming, and resource-intensive. Additionally, while the equipment is being fixed, industrial output declines. To reduce the frequency of breakdowns, we might frequently inspect the equipment and correct any minor issues that could later result in a complete breakdown. In terms of materials, labor expenses, and productivity loss due to scheduled downtime, these inspections are expensive. We must develop an inspection program that will provide us with the optimal balance between the frequency of inspections and the production in order to maximize the profit per unit time from the equipment over an extended period of time. Such a mechanism is seen in Figure 1.8. It may stop working for a number of reasons, including those

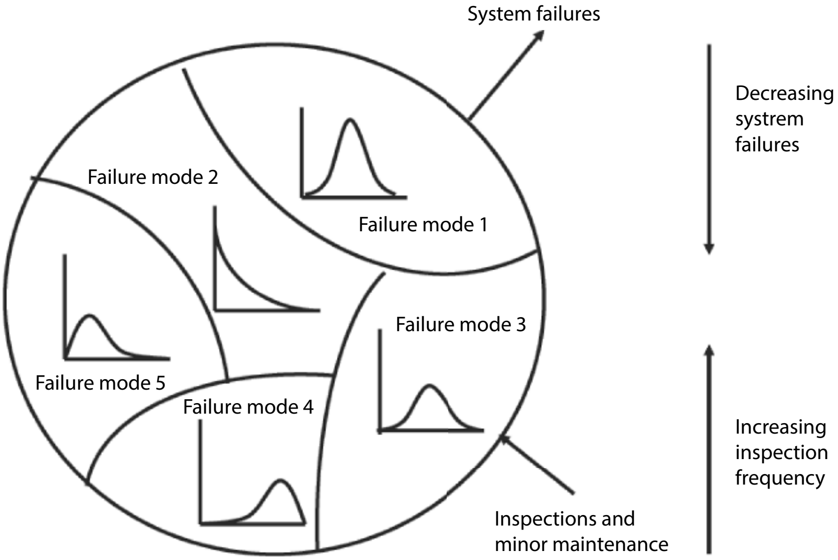

Figure 1.8 System failure (Jardine and Tsand, 2005).

caused by component 1, component 2, and so on. Each of these equipment failure reasons could have a unique independent failure distribution. It is believed that when inspection frequency or intensity increases, the frequency of equipment/system failures will decrease. It can be challenging to select the optimal frequency and intensity. Two models were suggested for this issue: one with the lowest cost and the other with the least amount of downtime.

Establishing an appropriate quantity of *emergency spares* that can be put into operation if a current long-life and highly dependable component breaks is a crucial aspect of spares management. Transformers in an electrical utility and electric motors in a conveyor system are two examples of such components. A few spare units might be maintained on hand to maintain a highly dependable service. The quantity of spares that should be stocked is an issue that needs to be answered in this section. It is necessary to indicate whether the spare part is one that is discarded after failure (a nonrepairable spare) or if it may be renewed and repaired after failure before being restocked in order to properly respond to the question (a repairable spare). Finally, it is important to comprehend the end result. For the purpose of determining the ideal number of both nonrepairable and repairable spares, four parameters will be taken into account in this section, which are as follows:

- Instantaneous reliability: Based on current circumstances, there is a probability that a spare is available. Depending on the source, this may also be referred to as long-term point availability, fill rate, or availability of stock.
- Interval reliability: This is the probability that there will not be a stock shortage at any point within a given time frame, like a year.
- Cost minimization: This includes the price of running out of a replacement part as well as the cost of buying and stocking spares.
- Availability: This is the proportion of a system's or unit's uptime (nondowntime) when the downtime is brought on by a lack of spare components.

When a nonrepairable component fails or is removed as a preventive measure, it is quickly replaced by one from the stock (the replacement time is presumed to be minimal), and the replaced component is not repaired. It is expected that the need for spare parts follows a Poisson process, which has found widespread use in the demand for emergency components.

The ordering of spare parts is covered in a block-based maintenance setting by Chelbi and Amk T-Kadi (2001). They simultaneously optimize the length of the replenishment cycles, the time between preventive maintenance checks, and the inventory level at which fresh orders for spare parts are placed. The investigations that follow take into account both maintenance and production. Integer linear programming is used by Najid, Alaoui-Selsouli, and Mohafid (2011) to consider the multi-item capacitated lot sizing problem in conjunction with routine preventive maintenance and minimal repairs after failure. Using a Markov decision process formulation, Borrero and Akhavan-Tabatabaei (2013) take into account a single-product workstation and incorporate maintenance expenses as well as either a cost for retaining inventory or a cost for not meeting demand while the machine is not in operation. To examine the joint optimization of an unstable manufacturing system's production, setup, and maintenance operations that produces two different types of products, Assid, Gharbi, and Hajji (2015) created a simulation model. Last but not least, Zhao, Mizutani, and Nakagawa (2015) take into account a unit processing a series of jobs with random processing times. The age replacement policy that causes jobs to be interrupted is contrasted with replacement after a set number of completed jobs and replacement following the end of the job, during which the maintenance age is attained.

Modern engineering systems and production procedures are becoming complex. As a result, managing system reliability in contemporary dynamic operating contexts becomes difficult (Lee, Ghaffari, and Elmeligy, 2011). Contrary to more conventional approaches that focus on time-based maintenance (TBM), *CBM* is a prominent strategy for the scheduling of maintenance interventions in this complex system (Jardine, Lin, and Banjevic, 2006).

Even in modern industrial systems, the competitiveness of industrial enterprises could gain significantly from an ideal CBM strategy (e.g., increasing system availability and consequent benefits for safety management (Harrou, Sun, and Madakyaru, 2016), reducing maintenance costs (Wiboonrat, 2018), and increasing product quality (Harrou, Sun, and Khadraoui, 2016)). Given that CBM is a well-established study area, the existence of earlier literature analyses is anticipated. In one of the studies of global CBM industrial practices up to 1994 (Martint, 1994), fundamental concepts including the requirement for scheduled maintenance, the purpose of CM, and the distinction between diagnosis and prediction were all introduced. More recent developments in data integration for CBM (Campos, 2009) and statistical data-driven approaches for the estimation of a system's remaining useful life (RUL) (Si *et al.*, 2011) are also examined in other studies, in addition to the methods typically used to monitor the health of mechanical systems and the decision models employed (A. H. C. Tsang, 1995).

At the moment, CBM is a well-liked predictive maintenance strategy. In recent decades, CBM techniques and procedures have been progressively enhanced. Due to the inherent benefits of using information retrieved from numerous sensors, sensor fusion techniques are increasingly and widely used. There has been a lot of focus on a number of approaches, including vibration, temperature, acoustic emissions, ultrasonic, oil debris, lubricant condition, chip detectors, and time/stress assessments. Since they are so good at representing machine performance, for instance, vibration signature analysis, oil analysis, and acoustic emissions, they have long been used successfully for prognostics. Three primary categories can be used to categorize current prognostic methods, which are as follows:

Model-based approach: This approach demands in-depth familiarity with the physical interactions and traits of each connected component in a system. The actual operating state is determined by measurements, and the expected operating state is derived from the values of the characteristics obtained from the physical model. The model-based method is typically tough, as the relationships and traits of all associated components in a system and its environment are frequently too complex to be represented by a model with an acceptable level of accuracy. Additionally, it is possible that the values of some process parameters or components are not readily available.

Data-driven approach: This approach demands a lot of historical information that depicts both "regular" and "faulty" operations. Instead of using prior process knowledge, it merely takes measurement data from the process itself to generate behavioral models. In this method, pattern recognition algorithms are frequently employed. The results of data analysis can be interpreted using general process knowledge, and then qualitative methods like fuzzy logic and artificial intelligence can be employed for decision-making to enable failure avoidance.

Hybrid approach: This approach combines sensor-based information with model-based information and employs both model-driven and data-driven methodologies to create prognostic outcomes that are more accurate and dependable.

The first industrial revolution began with corrective maintenance, and the second industrial revolution started with scheduled maintenance during the Ford automotive era. The two primary phenomena of the third industrial revolution are automation and computerization. With the aid of early automation and computerization, this has led to the usage of productive maintenance, also known as total productive maintenance or reliability-centered maintenance. The most advanced type of maintenance is "predictive maintenance," which was made possible by the relatively new Industry 4.0 concept, which fully utilized the benefits of cyber systems, cloud storage, and the Internet of Things. There is also an inverse relationship between the amount of maintenance and its "factor" OEE, as shown in Table 1.2 below. The overall effectiveness of the equipment increases as maintenance becomes more sophisticated.

The industry has a significant opportunity to deploy novel solutions to enhance operations and maintenance (O&M) practice given the improvement in instrumentation technologies, analytical software, and mathematical modeling. This has increased the level of optimism in several industries that still rely on traditional O&M procedures, encouraging those sectors to take advantage of multiple chances to lower the commercial risks connected with plant operations. Risk reduction and value creation are defined by technical circumstances and the safety integrity of operational plants or assets.

It suggests that a key component of risk mitigation and value creation initiatives is the operator's capacity to recognize equipment or system failures before any undesirable event or incident. In theory, this capability depends heavily on the technical information collected from the technical

Table 1.2 Correlation of the industrial revolution and maintenance (Coleman, 1956).

Industry revolution	**Industry 1.0**	**Industry 2.0**	**Industry 3.0**	**Industry 4.0**
Characteristics of the industrial revolution	Mechanization, steam power, weaving loom	Mass production, assembly lines, electrical energy	Automation, computers, electronics	Cyber-physical systems, IoT, networks, cloud, BDA
Type of maintenance	Reactive maintenance	Planned maintenance	Productive maintenance	Predictive maintenance
Inspection	Visual inspection	Instrumental inspection	Sensor monitoring	Predictive analysis
OEE (overall equipment effectiveness)	<50%	50–75%	75–90%	>90%
Maintenance team reinforcement	Trained craftsmen	Inspectors	Reliability engineers	Data scientists

apparatus and systems, as well as the operator's decision-support configuration. In order to gather the necessary technical data, critical systems and equipment must be properly instrumented. Analytical software with incorporated mathematical models is essential for the decision-making process. The core fundamentals of the O&M intervention process, which attempts to maintain or restore systems or equipment to a given condition so that the plant or asset conforms with a specific level of performance, are really presented in this explanation (see Figure 1.9). The technical tools in use and the analytical software and tools offer the essential engineering foundation for keeping track of the health of any specific asset's systems and equipment. The outcomes of this condition monitoring procedure are used as inputs by the asset operator or plant decision platforms and processes to make diagnostic or prognostic choices. Work orders are issued for the O&M crew whenever a fault or failure is about to occur. The most fundamental principle of the CBM approach is illustrated by this O&M intervention method. The widely adopted ideas of "e-maintenance" and "intelligent maintenance systems" can take advantage of the CBM platform's availability and manifest as sophisticated applications utilizing information and computer technology, durable technical infrastructures, and electronic devices and data acquisition technologies.

Studies have acknowledged that condition monitoring is not always accurate. These investigations take into account both the scenario in which the defective state is not detected and the scenario in which the inspection

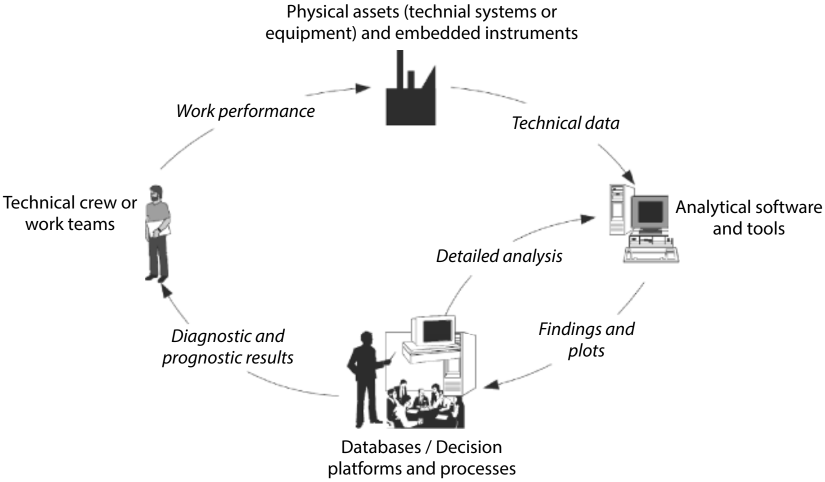

Figure 1.9 Basic O&M intervention process to retain or restore technical systems and equipment of an industrial asset in an acceptable technical condition.

inadvertently detects the defective state. Some publications take into account the proportional hazards model, in which the failure rate depends on the equipment's age and condition. Maintenance actions like overhaul and repair can be thought of as being equivalent to a replacement if it is reasonable to assume that they also restore equipment to the condition it was in before the repair or overhaul was performed. As a result, the following models can frequently be utilized to examine overhaul/repair issues in practice because this assumption is frequently a fair one.

1.3 Repair

In this section, we just provide a generic overview of various repair fundamentals with a specific introduction to imperfect repair. However, a detailed mathematical understanding of the imperfect repair process is provided in the second chapter.

The failure modes producing an asset's dysfunction determine the extent of repair that is required. Equipment failure can be classified into two categories: intermittent and extended failure. Intermittent failure lasts for a short time and occurs under certain conditions intermittently. Extended failure needs a certain corrective action or else it continues. Extended failure is further divided into two parts: partial and complete failure. Partial failures result in partial loss of function. Systems work but at a reduced capacity. Complete failures are the result of a total loss of function. The resource is totally broken and cannot be utilized until it is fixed. The further classification of complete and partial failures is mentioned in Figure 1.10.

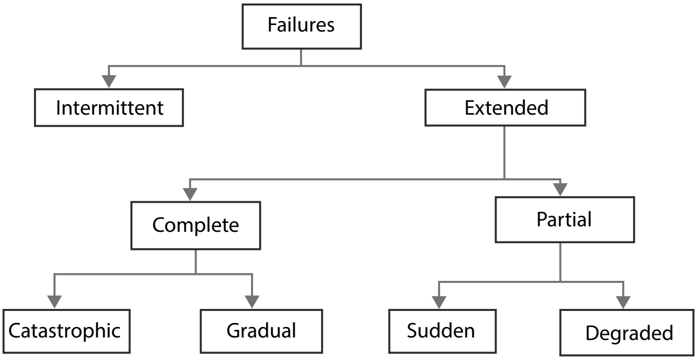

Figure 1.10 Types of failure.

When an item breaks down, it can be exceedingly expensive to repair it as well as to delay or cease production. Some failures are the result of mistakes made by people, unknown factors, or the normal wear and use of assets over many years of use. Many of these conditions are avoidable with preventive maintenance.

When a failure occurs, a system capable of being repaired rather than completely replaced can be said to be repairable. A system that cannot be repaired and must be replaced after malfunctioning is said to be nonrepairable. Many systems in the real world, including those in cars, planes, computers, and air conditioners, are repairable. The reliability of the repairable system made up of nonrepairable components will undoubtedly increase as a result of the increase in the reliability of the nonrepairable components.

Traditional reliability life or accelerated test data analysis, nonparametric or parametric, is based on a truly random sample drawn from a single population and independent and identically distributed (i.i.d.) assumptions on the reliability data obtained from the testing/fielded units. This i.i.d. assumption may also be valid, intuitively, on the first failure of several identical units, coming from the same design and manufacturing process, fielded in a specified or assumed to be in an identical environment. The life data of such items usually consist of an item's single failure (or very first failure for reparable items) and the times of some items still surviving, referred to as censoring or suspension. The reliability literature is vast to cover such aspects in reliability data analysis where the failure times are modeled by appropriate life distributions.

However, in repairable systems, one generally has times of successive failures of a single system, often violating the i.i.d. assumption. Hence, it is not surprising that statistical methods required for repairable systems differ from those needed in the reliability analysis of nonrepairable items. In order to address the reliability characteristics of complex repairable systems, a process rather than a distribution is often used. For a repairable system, time to next failure depends on both the life distribution (the probability distribution of the time to first failure) and the impact of maintenance actions performed after the first occurrence of a failure. The most popular process model is the power law process (PLP). This model is popular for several reasons. For instance, it has a very practical foundation in terms of minimal repair. Second, if the time to first failure follows the Weibull distribution, then the power law model repair governs each succeeding failure and adequately models the minimal repair phenomenon. In other words, the Weibull distribution addresses the very first failure, and the PLP addresses each succeeding failure for a repairable system. From this viewpoint, the PLP can be regarded as an extension of the Weibull distribution and a generalization of the Poisson process. Besides, the PLP is generally computationally easy in providing useful and practical solutions, which have been usually comprehended and accepted by the management for many real-world applications.

Minimal repair: Minimal repair restores the system to an "as bad as old condition" (ABAO). The assumption of minimal repair leads to the non-homogeneous Poisson process (NHPP). The NHPP is often a good model for repairable systems because it can model systems that are deteriorating or improving.

Renewal (or perfect) repair: Perfect repair restores the system to an "as good as new condition" (AGAN). If every repair is a renewal repair, then the times between failures are independent and identically distributed. Mathematically perfect repair is modeled using a renewal process (RP).

Imperfect repair: A failed unit is either repaired to a like-new condition or to a bad as old condition (i.e., a condition identical to that of a functioning unit of the same age). Specifically, under the imperfect repair model, a failed unit is given a perfect repair with probability p and an imperfect repair with probability $q = 1 - p$. In special cases, if $p = 0$, we have an NHPP, and if $p = 1$, we have a renewal process. A better understanding of these repair processes is shown below in Figure 1.11.

The following selected terms pertaining to the repairable systems are useful:

1. Point process
2. Counting random variable

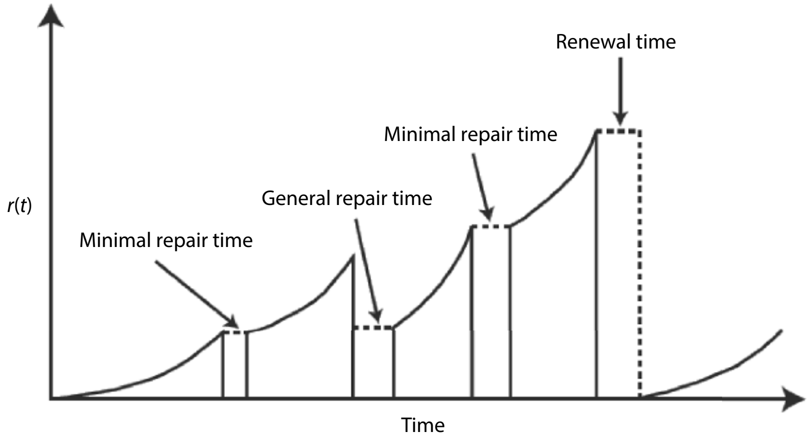

Figure 1.11 Minimal and general repair (Jardine and Tsand, 2005).

3. Mean function of the point process
4. Rate of occurrence of failures
5. Intensity function

All these terminologies are covered in detail in Chapter 2. Figure 1.12 summarizes the techniques in vogue for reliability analysis for both repairable and nonrepairable items, respectively.

Graphical methods for displaying data from repairable systems can be used to gain insight into the data and also to select a reasonable model. The first question one should ask when analyzing data from repairable systems is whether there is a trend in the times between failures. That is, are the times between failure getting longer? Or are they getting shorter? A simple, but powerful, graphical method is to plot the (global) failure time *t*, along the

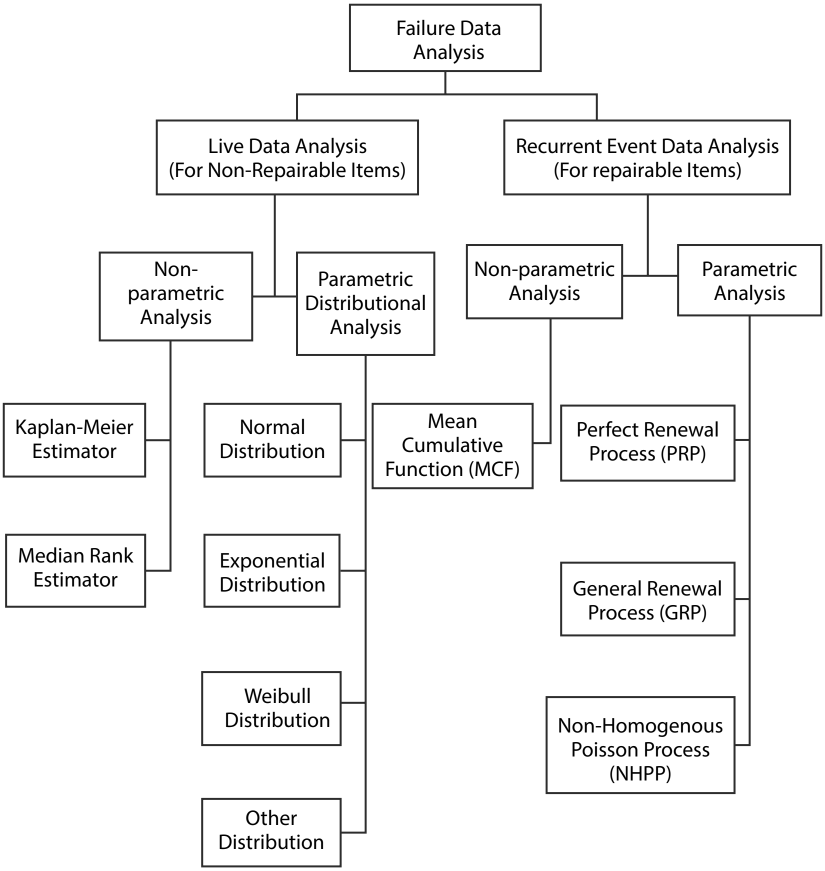

Figure 1.12 Various techniques for reliability analysis (Rai, Chaturvedi, and Bolia, 2020).

horizontal axis, and the cumulative number of failures through time t_i, $N(t)$, on the vertical axis. It is widely believed that Duane plots should be roughly linear if the power law process governs the failure times of the repairable system. Total time on test (TTT) (Bo Bergman, 2008) plots were developed for selecting a model for the lifetime distribution of a repairable system.

The homogeneous Poisson process (HPP) is the simplest statistical model for describing the occurrence of failures of a repairable system. The HPP, however, carries with it some strong assumptions that in practice are often clearly violated. The HPP implies that the system does not age in global time (failure time since the initial start-up), that is, the system does not deteriorate and it does not exhibit reliability improvement. The HPP also implies that the system does not wear out in local time (failure time since the previous failure), that is, during the times between failures. If either of these assumptions does not hold, then the HPP is not the appropriate model. Graphical methods are useful for determining the suitability of the HPP. If the plot of $N(\mathrm{t})/t$ versus t is linear, or if the Duane plot has a zero slope, then the HPP may be an appropriate model. It would then be useful to look at the times between failures to see if an exponential distribution can model them. If they can, then the HPP is appropriate; if they cannot, then a renewal process with a distribution besides the exponential would be appropriate.

A nonhomogeneous Poisson process is similar to an ordinary Poisson process, except that the average rate of arrivals is allowed to vary with time. Many applications that generate random points in time are modeled more faithfully with such nonhomogeneous processes. A homogeneous Poisson process has a constant intensity function, while a nonhomogeneous Poisson process can have a not constant intensity function.

Several statistical tests have been proposed for testing the null hypothesis that the process is an HPP against the alternative that there is a monotonic trend. Two types of tests for this purpose include the Laplace test, one of the earliest statistical tests of any kind, and the MIL-HDBK-189 test.

For a company or a competing manufacturer, the common concerns can be (Tobias, 2012; Nelson, 2003):

- The number of repairs, on average, for all systems at a specified operational time.
- Expected time to first repair, subsequent repairs, etc. Trends in repair rate or costs whether increasing, decreasing, or substantially constant.
- How to take decisions on burn-in requirements and maintenance or retirement.

- Is burn-in beneficial? How long and cost-effective would it be?
- How to compare different versions, designs, or performance of systems operating in different environments/regions, etc.

Each of the above questions and many more can be answered by the mean cumulative function (MCF) method based on the nonparametric graphical approach. It was observed that the MCF-based nonparametric method is a better choice to analyze the nature of fleet and system recurrence rates through the operational life of a product.

To simulate difficulties with system maintenance that can be fixed, the virtual age idea has been created. The idea of virtual age was introduced by Malik (1979) and Kijima (1989), respectively, when modeling repairable systems. Jiang (2001) proposed a repair limit for determining what maintenance action should be taken at the time of a maintenance issue. They did this by applying the virtual age idea. Figure 1.13 provides an illustration of the strategy. Here, it can be seen that the virtual age is on the x-axis and the real age (run time) of an object is on the y-axis at the top of the figure.

As a result, following the initial maintenance intervention, when the equipment is of age X1, it is of age V1 after the maintenance action. The virtual age of the item will be V2 once it has been in use for a further length of time X2. It is important to answer the following question: Which course of action should be followed when a maintenance intervention is required? Should the equipment undergo minimal, general, or complete renewal? How much money should be spent on each type of repair? Using the cost on the y-axis in the bottom half of the picture, we can see the repair limit notion in Figure 1.13 and answer this query. A minimal repair is conducted if the maintenance cost estimate is between zero and the limit C0. A general repair is carried out if the cost is between C0 and the cost boundary. A general repair rather than a total replacement should be done since, as shown in the figure, the cost of the first maintenance intervention is C1. As a result, the equipment's health is better than it was before the repair. A complete renewal should occur if the cost is higher than the boundary curve. Similar to this, a complete renewal is required if the equipment's running time crosses the line for preventive replacement.

The landmark papers by Kijima (1989) and Kijima M. (1986) modeled imperfect repair using the generalized renewal process (GRP) with the idea of the "virtual age." The paper spurred tremendous growth in the literature on imperfect maintenance as a consequence of which the GRP approach is well established. One reason for its ubiquitous popularity is its general approach to model repairable systems that can incorporate all of the five

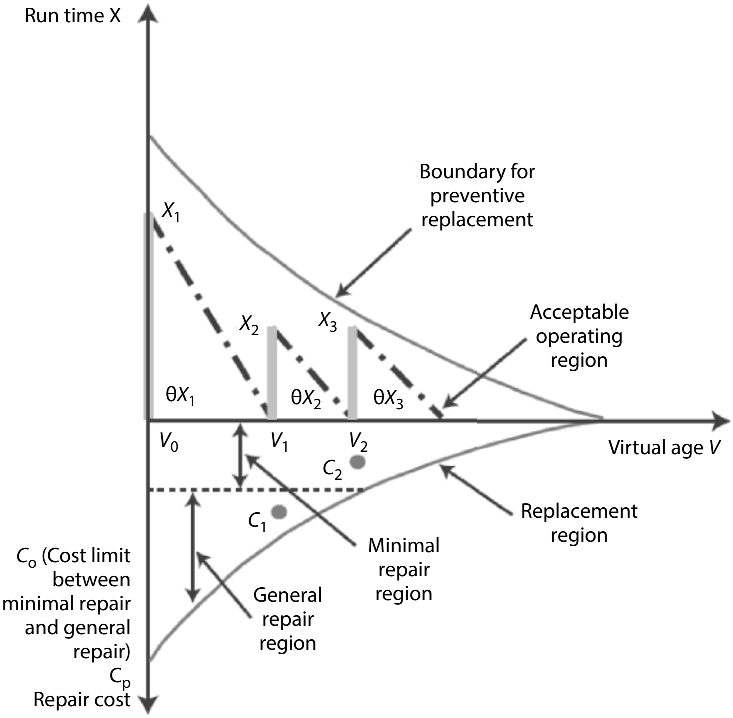

Figure 1.13 Optimizing minimal and general repair decisions (Jardine and Tsand, 2005).

after repair states in the same mathematical framework. The generalized renewal process framework is based on two broad approaches for imperfect repair: arithmetic reduction of age (ARA) and arithmetic reduction of intensity (ARI). In ARA models, the effect of repair is expressed by assuming a reduction in the actual age of the system and attaining an age termed as virtual age. ARA-based Kijima's virtual age models are the most widely cited and effective models in the literature. In the ARI approach, the repair effect is considered by the change induced on the failure intensity before and after failure. The parameters for the GRP model are also estimated using maximum likelihood estimation (MLE). Again, a detailed coverage in this regard has been provided in Chapter 1.

1.4 Overhaul

Overhaul is a detailed examination of all components and subsystems of the existing system and is a combination of preventive, corrective, and predictive maintenance. Overhaul includes thorough examination, dismantling of the whole system, repairs or replacements of the parts if required, and functional testing of systems, subsystems, and components, followed by reassembling of the complete system.

1.4.1 Overhauling: What Is It?

It is defined as a process of general maintenance performed on a system or other industrial equipment. The goal of overhauling is to keep the system in serviceable condition. Regular checks can prevent all kinds of critical damage. Machinery overhaul is usually performed by companies offering maintenance services. The frequency of overhauling can be agreed upon, and routine maintenance is usually scheduled for once a year. A more frequent equipment check is recommended for older machines and especially larger machines involving complex mechanisms. A major overhaul on a piece of equipment can also be considered as a planned corrective maintenance activity because it is undertaken at a predetermined time, usually after the dudes of the equipment are completed.

1.4.1.1 Benefits of Overhauling

(a) Cost-Effective
While it may seem unreasonable to further invest in a system that is still in operation, overhauling of the system protects the organization from undesirable expenses in the future. Replacing a few parts here and there is without a doubt more cost-effective than buying new machinery. A sudden breakdown of a machine can cause major financial losses in the industry. Even a single machine out of order means thousands and thousands of dollars lost in potential profit. Major global industrial companies recognize timely repair as a way to minimize costs and prevent critical equipment failures.

(b) Extended Life Length
Regular maintenance extends the life length of the equipment. Especially, predictive overhauling allows potential issues to be fixed even before the failure occurs. Naturally, when a piece of industrial equipment is in use, the mechanisms tend to wear down with time. However, extensive use of machinery which has shown signs of wear-down and damage can lead to a critical breakdown. Overhauling stops the extensive damage of the machinery and increases the lengths of its life cycle.

(c) Increased Performance
After years of extended use, the performance of the machinery is nowhere near its productivity at the beginning of the life cycle. With an overhaul, the machine's performance can be restored up to 100%. Such an impressive number basically means one can enjoy the benefits of using the almost brand-new equipment without any limitations. Increased performance of the machine represents the possibility to increase the level of production, hence expanding the company's profit.

(d) Reduced Labor Costs
Replacement of the entire piece of industrial equipment is essentially more time-consuming than a small repair or replacement of just one part. Instead of replacing the entire machine with a new one, only certain parts are replaced or even repaired. Predictive maintenance reduces the number of critical "call-outs" and naturally the amount of time spent on a service call.

1.4.1.2 Factors Determining the Performance of the Overhaul

(a) Time Taken for Completing the Overhaul
Overhaul activities should be carried out in such a way that each activity carried out in the overhaul is done with optimum time and cost so that the overhaul is completed in optimum time.

(b) The Quantum of the Job Carried Out
This factor describes the extent to which the overhaul is carried out, i.e., the level of disassembly and assembly done during the overhaul, whether the disassembly takes place at the subsystem level, component level, etc.

(c) The Extent to Which the System Is Restored to as Good as New State
During the overhaul, the components are replaced or repaired based on their condition found during the inspection. So, it is important to note that not all the components of the system are replaced or repaired. So, the state of the system after the overhaul is between as bad as old and as good as new condition and the extent to which the system is restored to the as good as new state depends on the extent of the activities performed during the overhaul process.

(d) The Guaranteed Period of Failure Free Operation
After the overhaul is completed, it is important to find the extent to which the overall life of the system can assure no failure of the system during the extended life of the system.

1.4.1.3 Overhauling of the System in Stages

Overhauling involves several stages as shown in Figure 1.14 and these are explained in subsequent paragraphs.

(a) Inspection
First of all, the machine will be thoroughly inspected. Experienced maintenance crews perform an inspection on the overhauled machine under production conditions. It means that the machine's performance is monitored while the machine is in use. Such a procedure allows to allocate any issues and perform the troubleshooting more effectively.

(b) Disassembly
After the initial inspection, the piece of equipment should be taken apart. Disassembly is crucial for further checking and for the next steps of the overhauling process, such as repair. A skilled maintenance worker is capable of putting the machine down efficiently, indicating which parts of the equipment need to be replaced or repaired.

(c) Repair
Depending on the issue, the machine is either repaired or certain damaged parts are replaced. This step once again proves how effective overhauling is as opposed to replacing the whole piece of equipment at once. Replacement of parts might take longer than a simple repair, as the spare parts might need to be ordered from a manufacturer.

(d) Reassembly
Following the successful replacement of spare parts, reassembly of the whole mechanism is performed. Being one of the final steps, reassembly is crucial for the functioning of the equipment. A certain skill is surely needed to perform reassembly, so it is best handled by professionals.

(e) Testing
This is the final step that concludes the overhauling process. Without testing, it is naturally impossible to identify if the performed repair was effective. During testing, the retrofit is either proclaimed successful or—less frequently—the process goes back to the starting point (inspection).

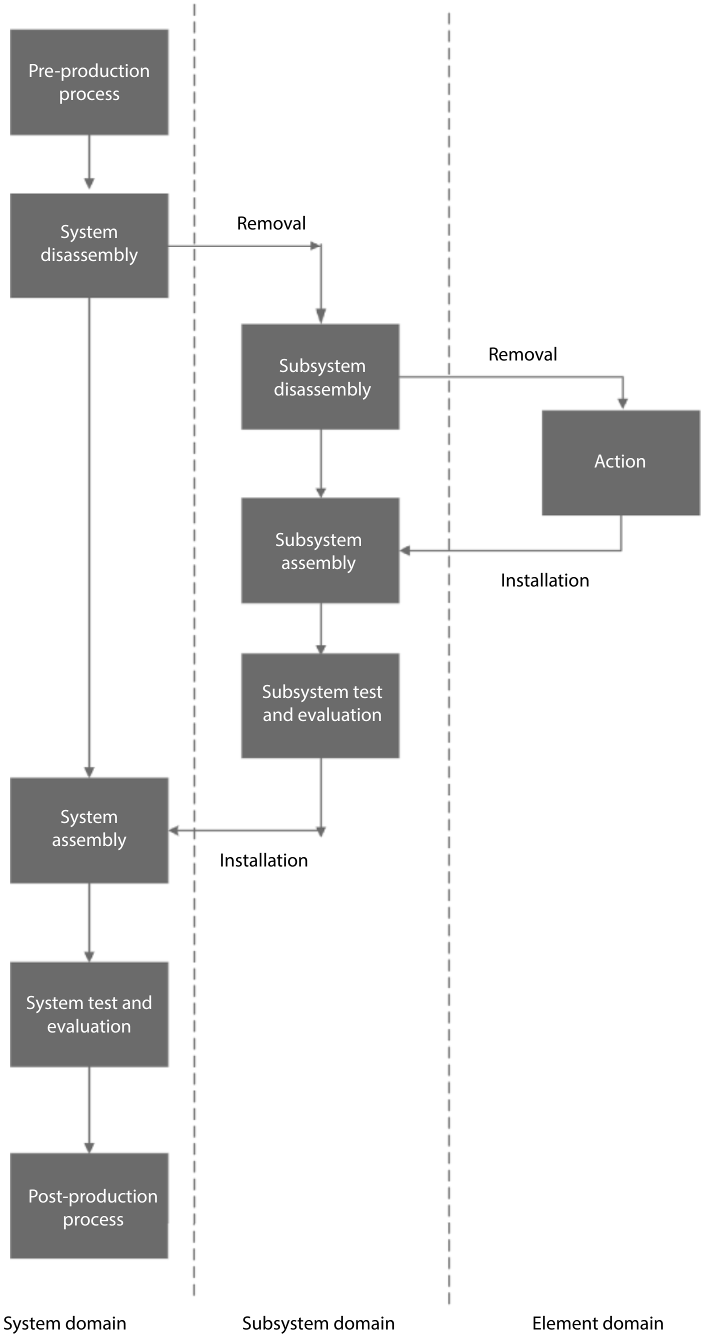

Figure 1.14 Major overhaul flowchart.

1.5 Chapter Summary

Maintenance, repair, and overhaul facilities are established to undertake reliability studies on repairable systems. In this chapter, the authors provide a preview of the fundamental understanding of MRO so that it will be easier to assimilate the comprehension of the advanced reliability techniques to deal with repairable systems, which has been attempted in this book through subsequent chapters. This chapter provides a pointer on the basics of imperfect repair, and a detailed understanding of mathematical concepts is covered in the subsequent chapters.

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