1
Introduction to Repairable Systems

1.1 Introduction

A system is a collection of mutually related items, assembled to perform one or more intended functions. Any system majorly consists of (i) items as the operating parts, (ii) attributes as the properties of items, and (iii) the link between items and attributes as interrelationships. A system is not only expected to perform its specified function(s) under its operating conditions and constraints but also expected to meet specified requirements, referred as performance and attributes. The system exhibits certain behavioural pattern that can never ever be exhibited by any of its constituent items or their subsets. The items of a system may themselves be systems, and every system may be part of a larger system in a hierarchy. Each system has a purpose for which items, attributes, and relationships have been organized. Everything else that remains outside the boundaries of system is considered as environment from where a system receives input (in the form of material, energy, and/or information) and makes output to the environment which might be in different form as that of the input it had received. Internally, the items communicate through input and output wherein output(s) of one items(s) becomes the input(s) to others. The inherent ability of an item/system to perform required function(s) with specified performance and attributes when it is utilized as specified is known as *functionability* [1]. This definition differentiates between the terms functionality and functionability where former is purely related to the function performed whereas latter also takes into considerations the level of performance achieved.

Despite the system is functionable at the beginning of its operational life, we are fully aware that even after using the perfect design, best technology available for its production or the materials from which it is made, certain irreversible changes are bound to occur due to the actions of various interacting and superimposing processes, such as corrosion, deformations, distortions, overheating, fatigue, or similar. These interacting processes are the

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main reason behind the change in the output characteristics of the system. The deviation of these characteristics from the specifications constitutes a *failure*. The failure of a system, therefore, can be defined as an event whose occurrence results in either loss of ability to perform required function(s) or loss of ability to satisfy the specified requirements (i.e., performance and/or attributes). Regardless of the reason of occurrence of this change, a failure causes system to transit from a state of functioning to a state of failure or state of unacceptable performance. For many systems, a transition to the unsatisfactory or failure state means retirement. Engineering systems of this type are known as *non-maintained* or *non-reparable* system because it is impossible to restore their functionability within reasonable time, means, and resources. For example, a missile is a non-repairable system once launched. Other examples of non-repairable systems include electric bulbs, batteries, transistors, etc. However, there are a large number of systems whose functionability can be restored by effecting certain specified tasks known as *maintenance tasks*. These tasks can be as complex as necessitating a complete overhaul or as simple as just cleaning, replacement, or adjustment. One can cite several examples of repairable systems one's own day-to-day interactions with such systems that include but not limited to automobiles, computers, aircrafts, industrial machineries, etc. For instance, a laptop, not connected to an electrical power supply, may fail to start if its battery is dead. In this case, replacing the battery—a non-maintained item—with a new one may solve the problem. A television set is another example of a repairable system, which upon failure can be restored to satisfactory condition by simply replacing either the failed resistor or transistor or even a circuit board if that is the cause, or by adjusting the sweep or synchronization settings.

The system, in fact, wavers and stays between satisfactory and unsatisfactory states during its operational life until a decision is taken to dispense with it. The proportion of the time, during which the system is functionable, depends on the interaction between the inherent characteristics of a system from the design and utilization function given by the users' specific requirements and actions. The prominent inherent characteristics could be *reliability*, *maintainability*, and *supportability*. Note that these characteristics are directly related to the frequency of failures, the complexity of a maintenance task, and ease to support that task. The utilization characteristics are driven by the users' operational scenarios and maintenance policy adopted, which are further supported by the logistics functions, which is related to the provisioning of operational and maintenance resources needed. In short, the pattern followed by an engineering system can be termed as funtionability profile whose specific shape is governed by the inherent characteristics of design and system's utilization. The metric

Availability or its variants quantitatively summarize the functionability profile of an item/system. It is an extremely important and useful measure for reparable systems; besides, a technical aid in the cases where user is to make decisions regarding the acquisition of one item among several competing possibilities with differing values of reliability, maintainability, and supportability. Functionability and availability brought together indicates how good a system is. It is referred as *system technical effectiveness* representing the inherent capability of the system. Clearly, the biggest opportunity to make an impact on systems' characteristics is at the design stage to won or lost the battle when changes and modifications are possible almost at negligible efforts. Therefore, the biggest challenge for engineers, scientists, and researchers has been to assess the impact of the design on the maintenance process at the earliest stage of the design through field experiences, analysis, planning and management. And, the repairable system analysis is not just constricted on finding out the reliability metrics.

Most complex systems, such as automobiles, communication systems, aircraft, engine controllers, printers, medical diagnostics systems, helicopters, train locomotives, and so on so forth are repaired once they fail. In fact, when a system enters into utilization process, it is exposed to three different performance influencing factors, *viz.*, operation, maintenance, and logistics, which should be strategically managed in accordance with the business plans of the owners. It is often of considerable interest to determine the reliability and other performance characteristics under these conditions. Areas of interest may include assessing the expected number of failures during the warranty period, maintaining a minimum reliability for an interval, addressing the rate of wear out, determining when to replace or overhaul a system, and minimizing its life cycle costs.

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. Life data of such items usually consists of an item's single failure (or very first failure for reparable items) times with some items may be still surviving-referred as censoring or suspension. The reliability literature is in plenty to cover such aspects in reliability data analysis where the failure times are modeled by appropriate life distributions [2].

However, in repairable system, 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 system differ from those needed in reliability analysis of non-repairable 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*—a situation when the repair of a failed system is just enough to get the system operational again by repair or replacement of its constituent item(s). 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 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.

The usual notion and assumption of overhauling of a system is to bringing it back to "as-good-as-new" (AGAN) condition. This notion may not be true in practice and an overhaul may not achieve the system reliability back to where it was when the system was new. However, there is concurrence among all the stakeholders that an overhaul indeed makes the system more reliable than just before its overhaul. For systems that are not overhauled, there is only one cycle and we are interested in the reliability characteristics of such systems as the system ages during its operational life. For systems that are overhauled several times during their lifetime, our interest would be in the reliability characteristics of the system as it ages during its cycles, i.e., the age of the system starts from the beginning of the cycle and each cycle starts with a new zero time.

1.2 Perfect, Minimal, and Imperfect Repairs

As discussed earlier, a repairable system is a system that is restored to its functionable state after the loss of functionability by the actions other than replacement of the entire system. The quantum of repair depends upon various factors like criticality of the component failed, operational status of the system, risk index, etc. Accordingly, the management takes a decision on how much repair a system has to undergo. The two extremes of the repair are perfect and minimal repairs. A system is said to be perfectly repaired, if the system is restored to AGAN condition (as it is replaced with a new one). Normally, a perfect repair in terms of the replacement is carried out for very critical components, which may compromise operation ability, safety of the system, and/or personnel working with the system. On the other hand, a system is said to be minimally repaired, if its working state is restored to "as-bad-as-old" (ABAO). This type of repair is undertaken when there is heavy demand for the system to work for a finite time or the system will be undergoing preventive maintenance shortly or will be scrapped soon.

Any repair other than perfect and minimal repair comes under imperfect repair. Most of the repairs observed in *day-to-day* systems are imperfect repairs, i.e., a system is neither restored to AGAN conditions nor to ABAO conditions. The three types of repairs are pictorially represented in Figure 1.1.

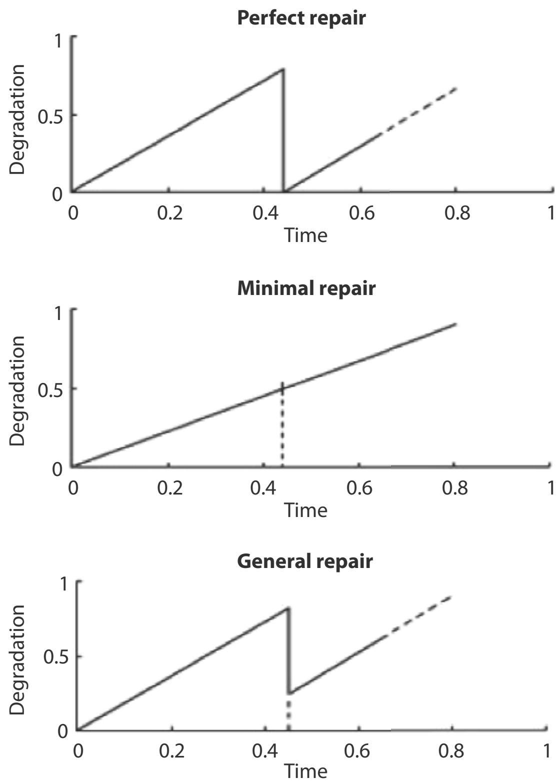

Figure 1.1 Types of repair.

It can be seen from Figure 1.1 that in case of perfect repair, the system is rendered "AGAN" and the life starts at zero in the time scale signifying that the performance degradation is completely restored. In case of minimal repair, after the system is subjected to a repair action, its age remains same as before the repair action and there is no restoration of life below the previous age. So far the general repair is concerned, some of its life is renewed and the system starts functioning after being restored to somewhere between "ABAO" and "AGAN" state.

Figure 1.2 summarizes the techniques in vogue for reliability analysis for both repairable and non-repairable items, respectively.

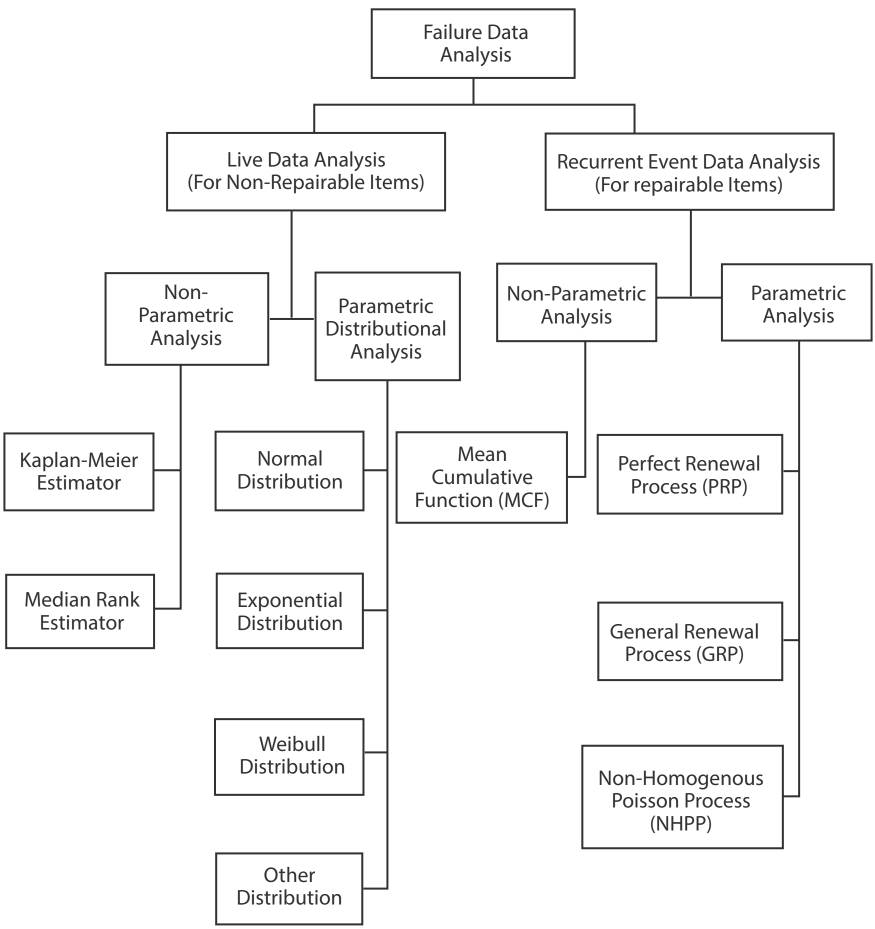

Figure 1.2 Various techniques for reliability analysis.

A *renewal process* (RP) is a counting process where the *inter-occurrence times* are stochastically *i.i.d.* with an arbitrary life distribution. Under the RP, a single distribution can characterize the time between failures (TBF), and the frequency of repair appears constant. The non-renewal behavior occurs if this frequency of repairs increases (deteriorating systems) or decreases (system improving) influencing the corresponding maintenance costs. The *homogeneous Poisson process* (HPP) describes a sequence of statistically *i.i.d.* exponential random variables. Conversely, a non-homogeneous Poisson process (NHPP) [3, 4] describes a sequence of random variables that are neither statistically independent nor identically distributed. The NHPP is often used to model repairable systems that are subject to minimal repair. The generalized renewal process (GRP) allows the goodness of repairs within two extremities, *viz.*, AGAN repair (RP) to the same-as-old repair (NHPP). The GRP is particularly useful in modeling the failure behavior of a specific unit and understanding the effects of repair actions on the age of that system. An example of a system to which the GRP is especially applicable is a system, which is repaired after a failure and whose repair neither brings the system to an AGAN or an ABAO condition, but instead partially rejuvenates the system. Therefore, one should be cautious on the fact that without looking at the actual behavior of the data may lead to underestimation or overestimation of engineering metrics.

The analysis by employing the parametric methods on scenarios of failure-repair requires a certain degree of statistical knowledge, the ability to solve complex equations and verification of distributional assumptions. Further, these equations cannot be solved analytically and require an iterative procedure or special software. Besides, parametric approaches are computationally intensive and not intuitive to a novice or an average person. The analysis of events, irrespective of the nature of the system-reparable or not reparable, should take an analysis path from non-parametric to versatile parametric model with graphical analysis being a common denominator. Undoubtedly, the choice of method depends on the data available and the questions we wish to answer.

1.3 Summary

A repairable system is a system that is restored to its functionable state after the loss of functionability by the actions other than replacement of the entire system. The two extremes of the repair are perfect and minimal repairs. A system is said to be perfectly repaired, if the system is restored to AGAN condition (as it is replaced with a new one). On the other hand, a system is said to be minimally repaired, if its working state is restored to ABAO. Any repair other than perfect and minimal repair comes under imperfect repair. Most of the repairs observed in *day-to-day* systems are imperfect repairs, i.e., a system is neither restored to AGAN conditions nor to ABAO conditions. The RP is used to model AGAN condition. The NHPP is often used to model repairable systems that are subject to minimal repair. The GRP allows the goodness of repairs within two extremities, *viz.*, AGAN repair (RP) to the same-as-old repair (NHPP).

The next chapter describes the mean cumulative function (MCF) based graphical and non-parametric methods for repairable systems.

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